

# Boosting Higgs Discovery

Graham Kribs

Fermilab & U Oregon

Wine & Cheese 4 Feb 2011





# Ben Lee



1935–1977

- First paper with “Higgs phenomena” in title (1971)
- Upper bound on Higgs mass from unitarity “Lee-Quigg-Thacker bound”
- Classic “Lee-Weinberg” bound on neutral lepton masses
- Series on renormalizability of gauge theories

“I, personally, know of no one who claimed to understand the details of ‘t Hooft’s paper. Rather we all learned it from Ben Lee, who combined insights from his own work”

Politzer Nobel Lecture



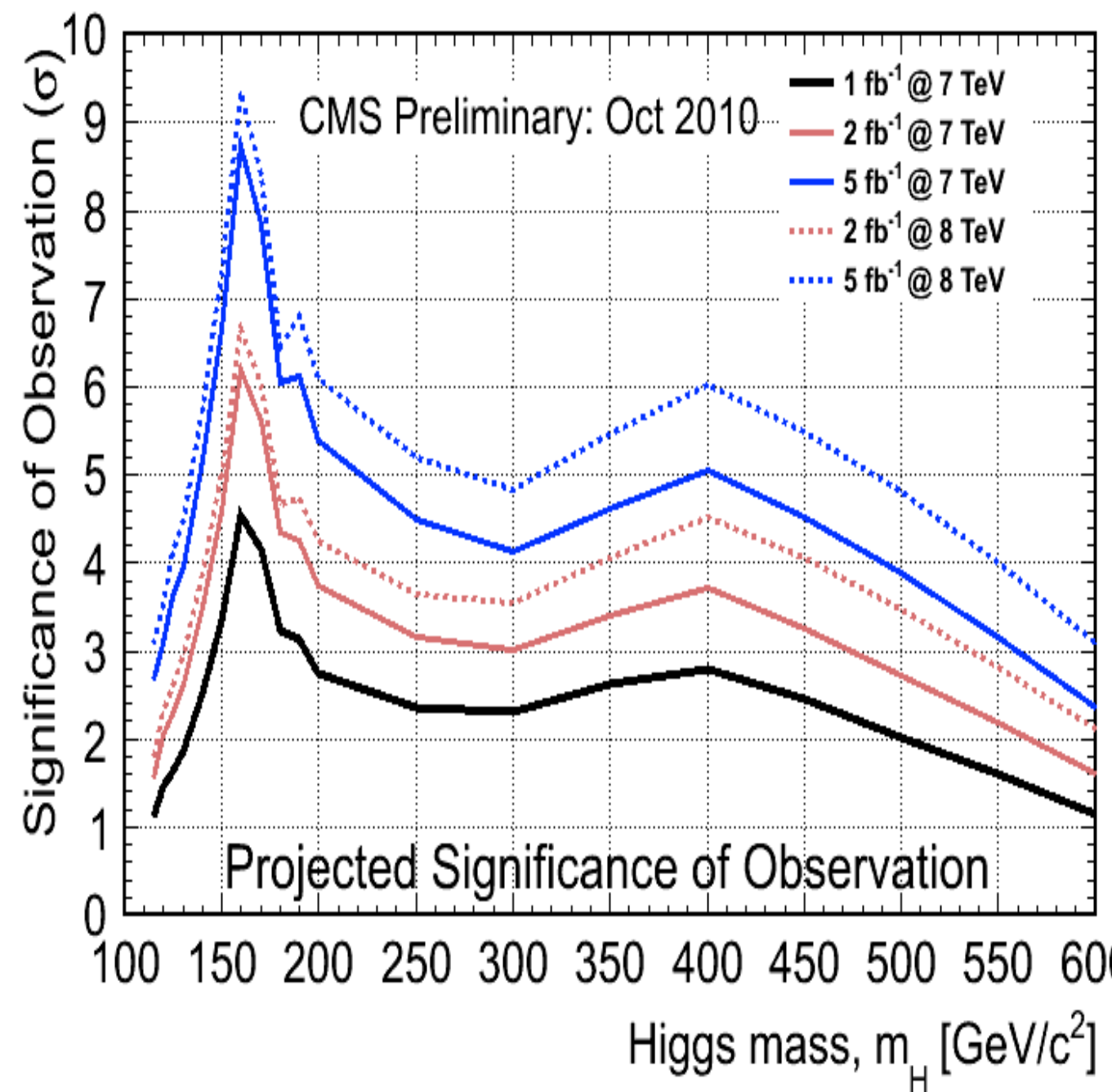
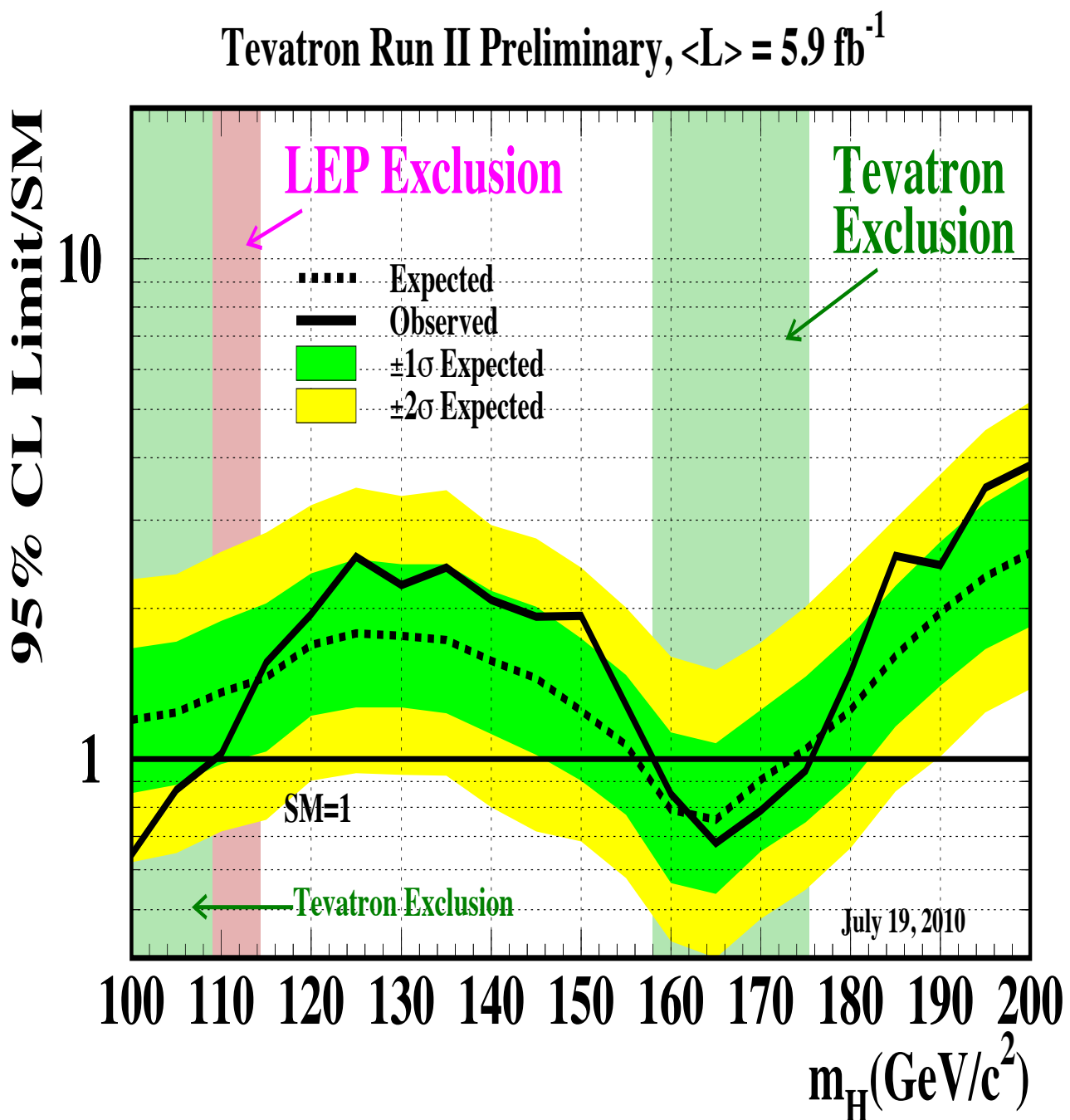
# Outline

- Higgs in Standard Model
- Jet Substructure applied to  $h \rightarrow b\bar{b}$  @ LHC
- Higgs in new physics:
  - i) SUSY
  - ii) top-partners
- Discovery of Higgs in new physics events
- Summary

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# Era of Higgs Physics

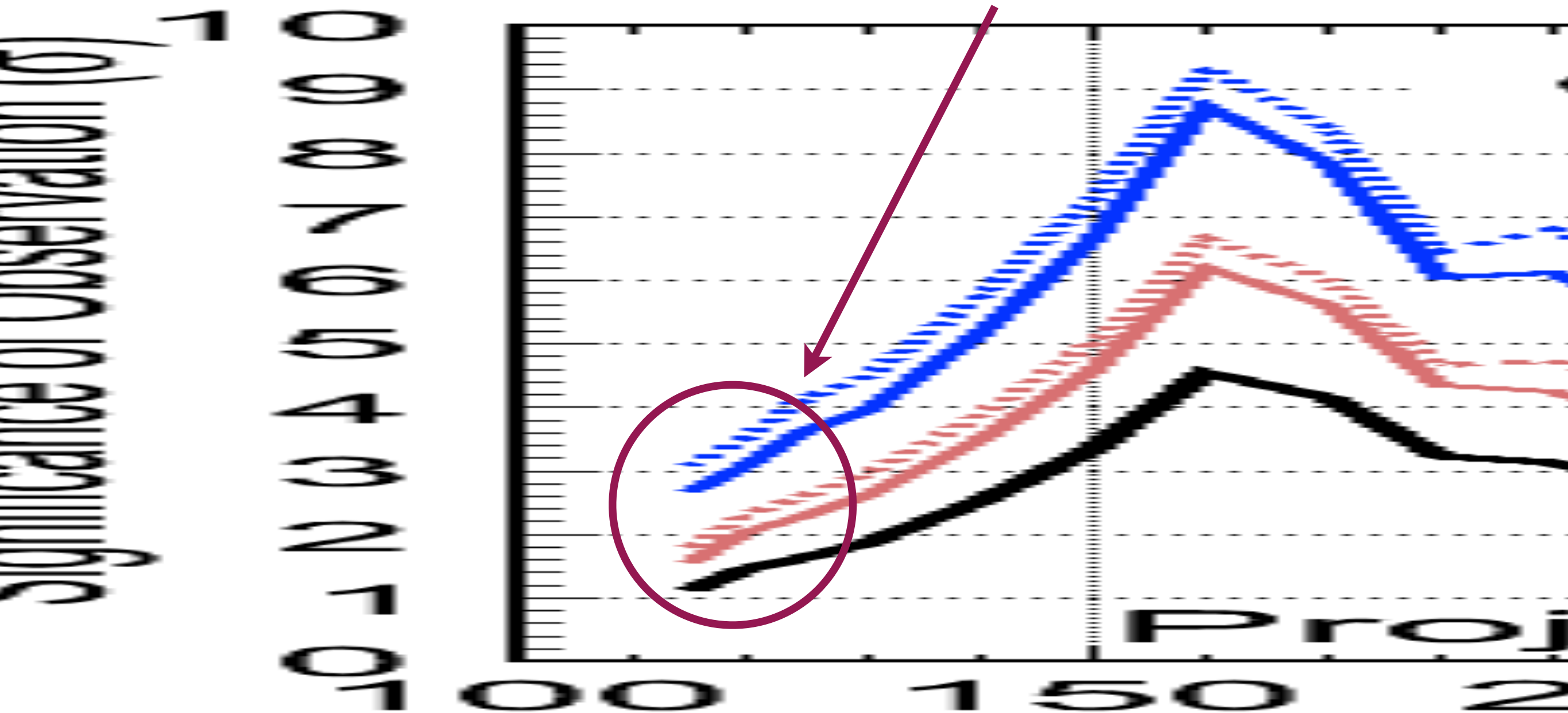


1007.4587

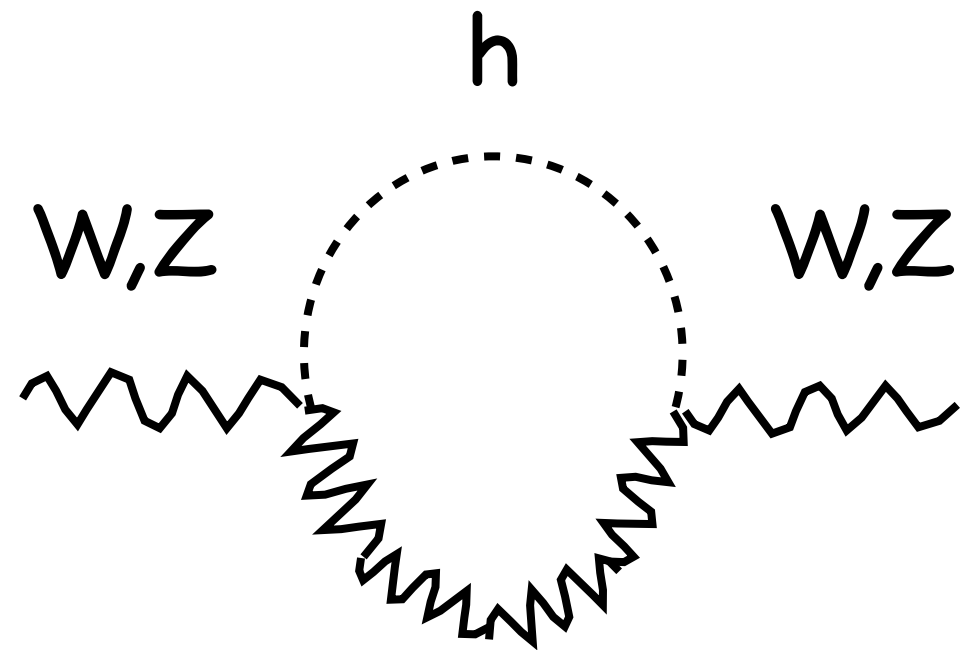
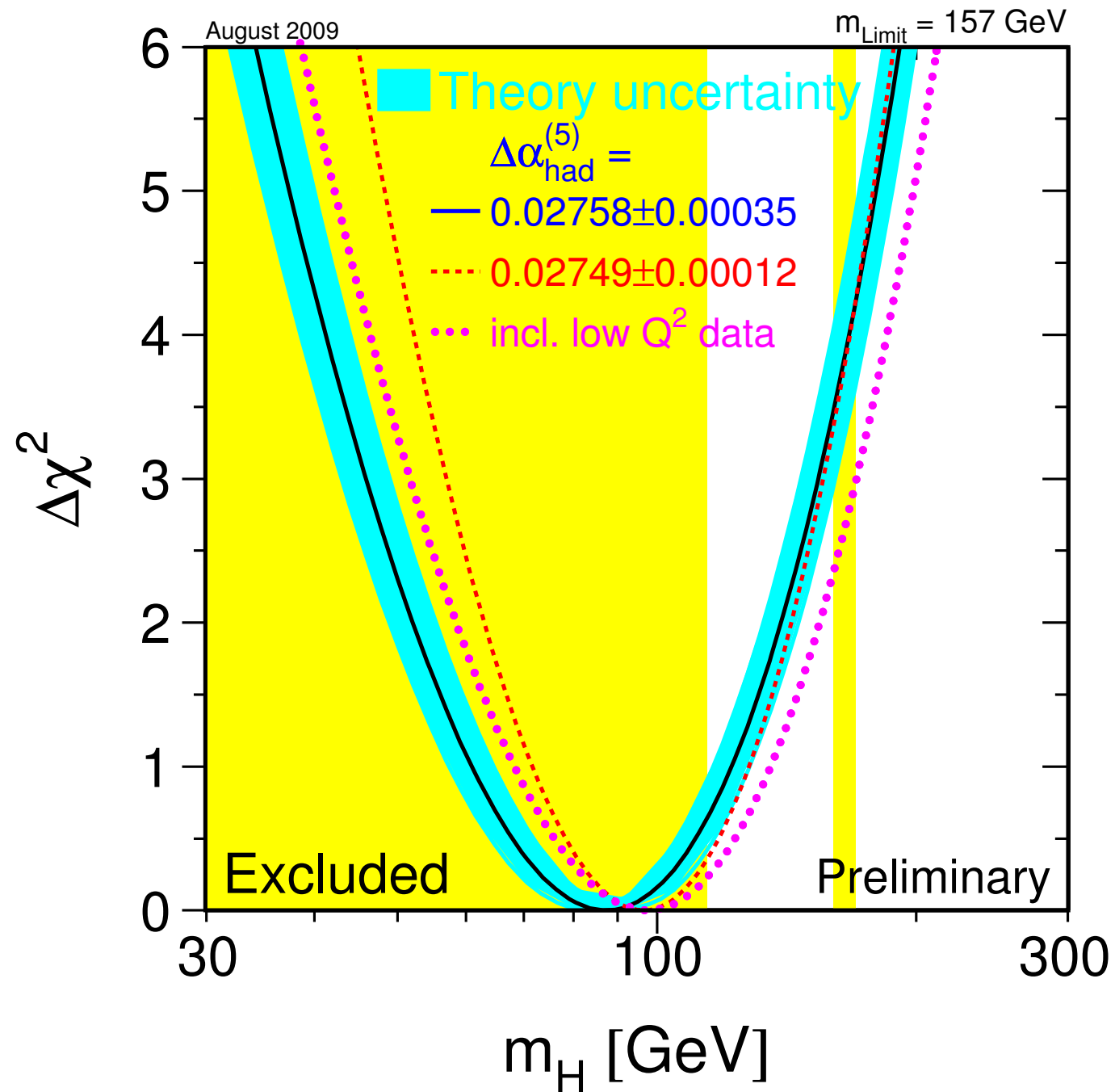
updated CMS NOTE-2010/008

“Almost” discovery (or rule out)  
within 1-2 years

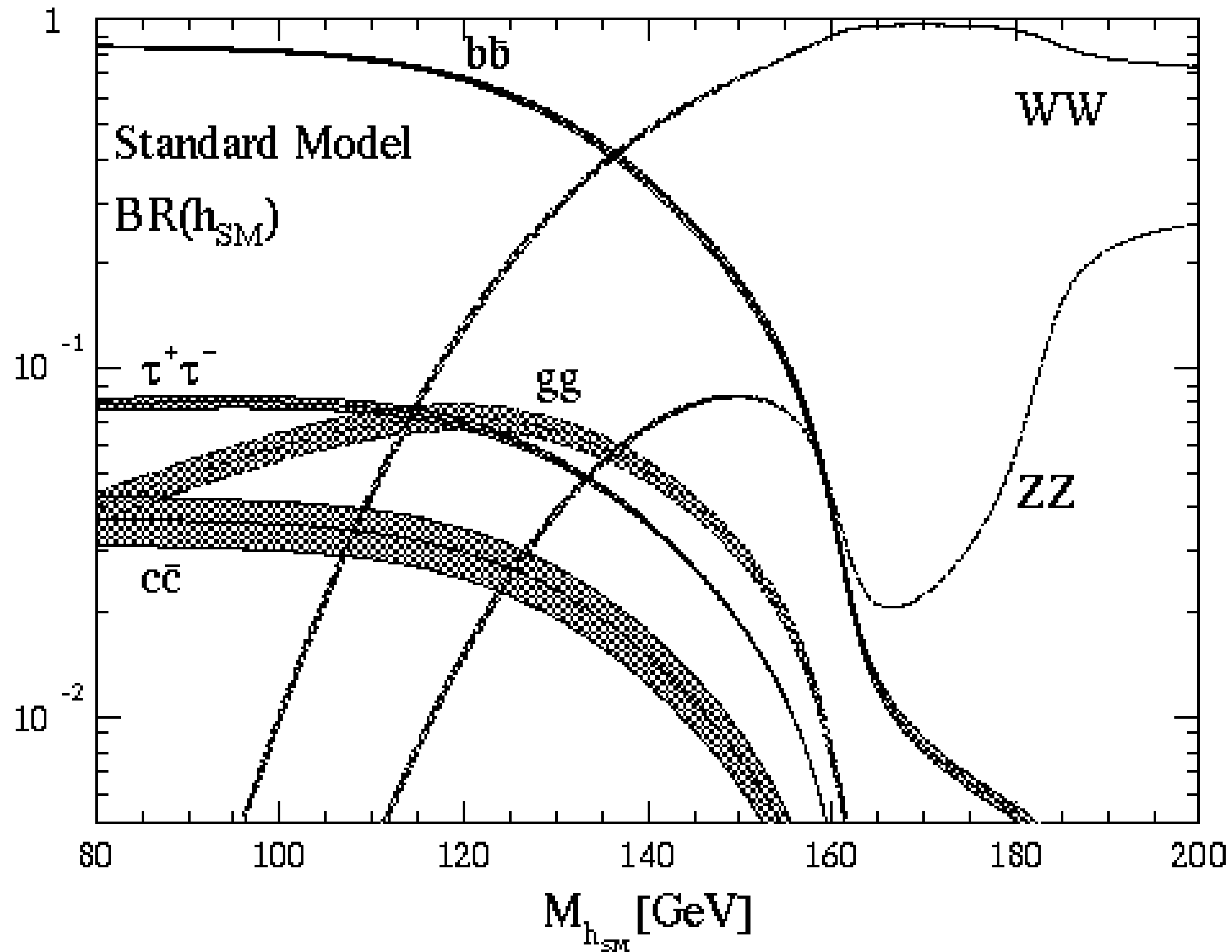
Except!



# EW Precision $\Rightarrow$ SM Higgs is Light

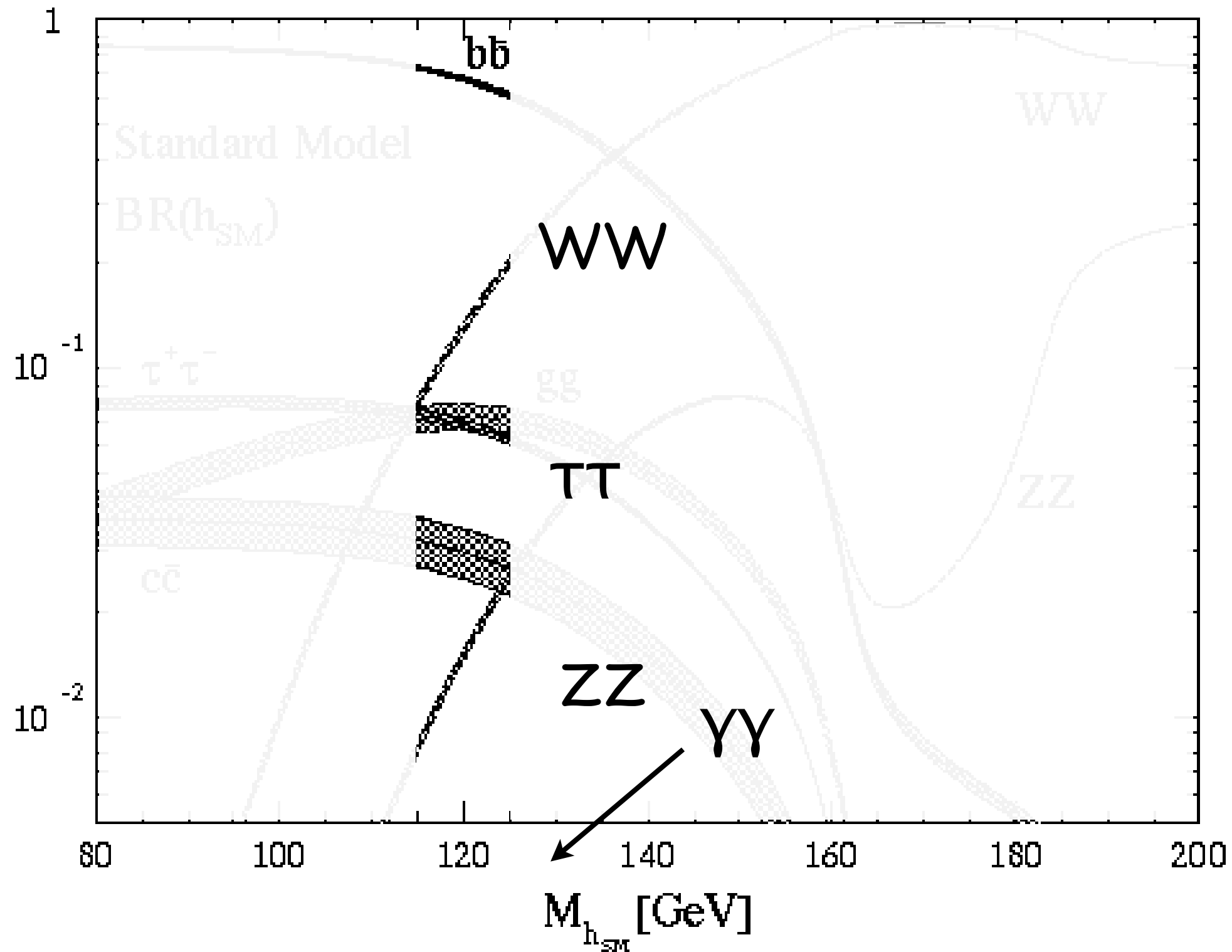


# Branching Ratios of SM Higgs



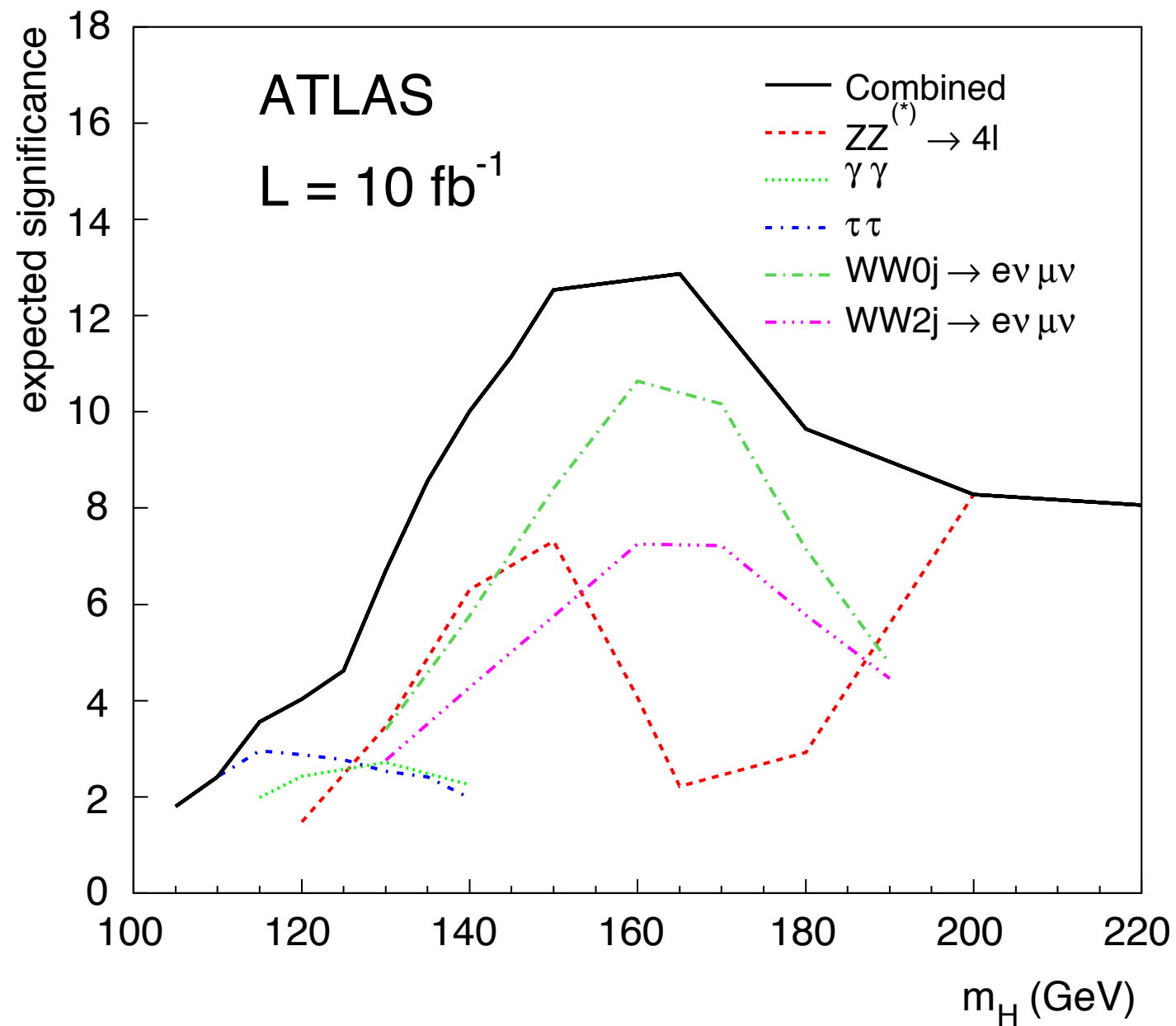


Pesky region is  $115 < m_h < 125$  GeV



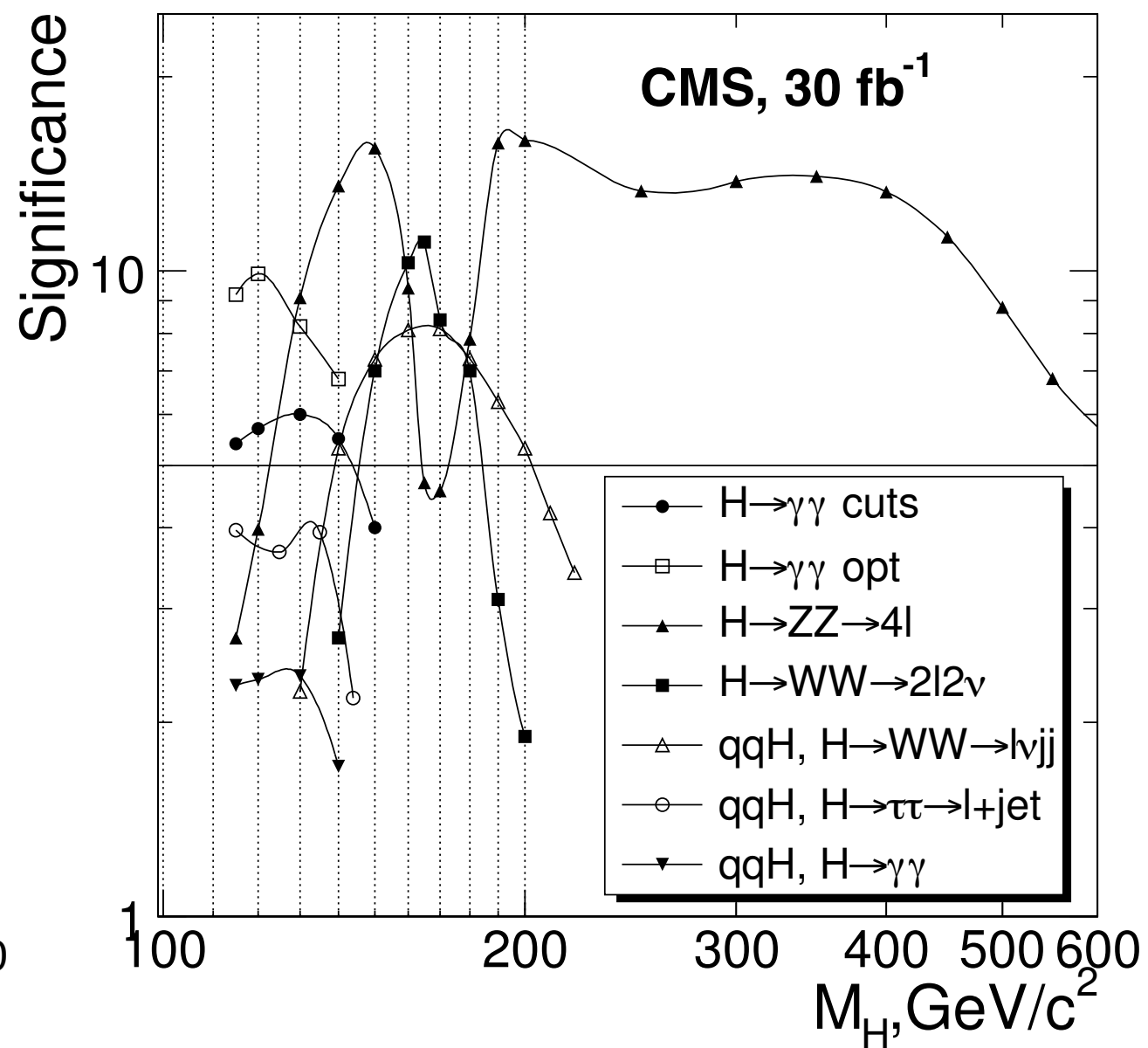
# ATLAS TDR 2009

## 10 fb<sup>-1</sup>

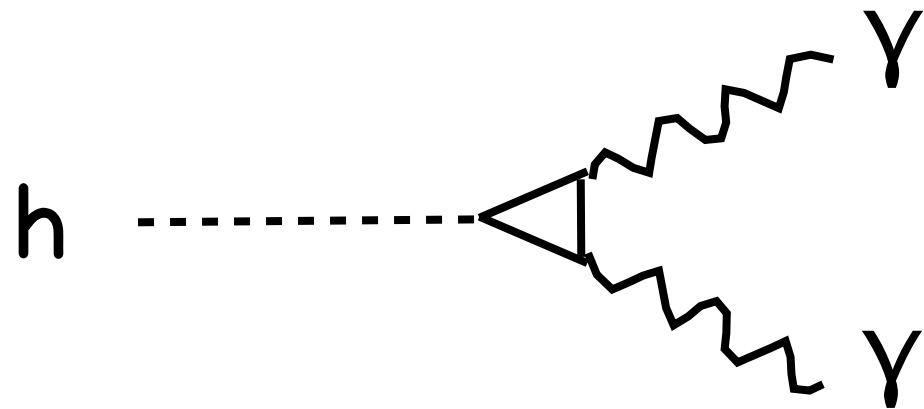


# CMS TDR 2006

## 30 fb<sup>-1</sup>

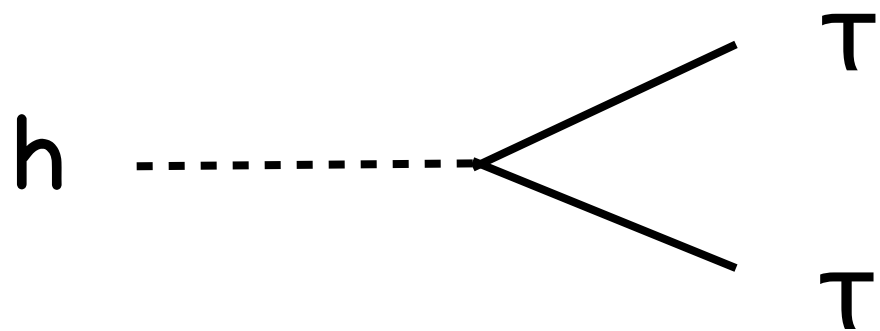


# Search Channels $115 < m_h < 125 \text{ GeV}$



$$\text{BR}(h \rightarrow \gamma\gamma) \approx 1-2 \times 10^{-3}$$

loop suppressed



$$\text{BR}(h \rightarrow \tau\tau) \approx 5-7 \times 10^{-2}$$

$\kappa_\tau \approx 0.01$  suppressed

Until 2008, was thought that

$$\text{BR}(h \rightarrow b\bar{b}) \approx 0.7-0.9$$

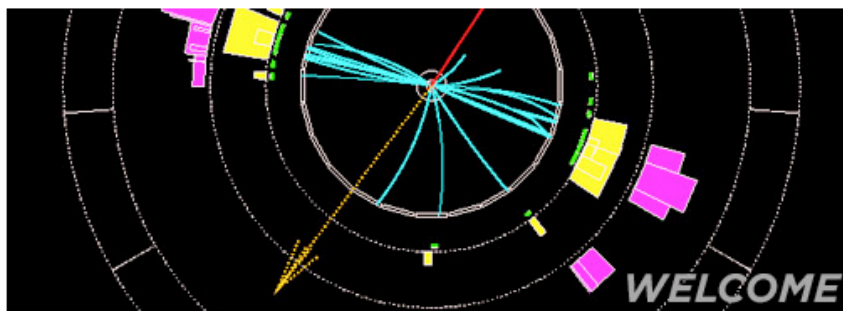
lost in the QCD background.

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# Jet Substructure

Much activity in past 2-3 years...



## Giving New Physics a Boost

Thursday and Friday, July 9-10, 2009 from 8:00 am to 5:00 pm.

Kavli Auditorium

SLAC National Accelerator Laboratory

## Joint Theoretical-Experimental Workshop on Jets and Jet Substructure at the LHC

University of Washington  
January 11-15, 2010

The next workshop is on the topic of jets at the LHC. The special focus concerns strategies to use jet substructure to both rediscover the Standard Model (e.g., can we find top quarks as single jets in the first LHC data, or at Fermilab?) and to search for new physics. The workshop will also include a discussion of the challenging issue of calibrating the measurements of jet substructure (e.g., masses) on the experimental side, and better formalisms for describing jet substructure on the theory side.

## BOOST2010

- Home Page
- Agenda
- Participants
- Transport
- Accommodation
- Local Facilities
- Committee
- Contact
- Previous Meetings
- Poster
- Payment

Dates: 22-25 June 2010

Boost 2010 is a continuation of the successful small-scale workshop **Boost 2009** held at SLAC in July 2009. The workshop addresses new physics signatures involving highly boosted objects which can evade standard event reconstruction techniques due to their decay products being observed as single objects within the detector.

The purpose of the workshop is to bring together leading theorists and experimentalists with the aim of better understanding the physics behind these signatures and how to detect them. The topics covered include, but are not limited to, boosted tops ("t-tagging"), "lepton jets" and boosted Higgs, W and Z bosons. This workshop will particularly explore what can be learnt about the tools and theory, and what measurements need to be made in the coming year before Boost 2011, as the LHC era begins.

In addition to talks, there will be discussion sessions. This discussion will be broadly divided into two working groups: one dedicated to boosted states decaying to leptons and one dedicated to boosted states decaying to hadrons.

## Northwest Terascale Research Projects

*Using jet substructure to find new physics at the LHC*

University of Oregon

31 January - 4 February 2011

## BOSTON JET PHYSICS WORKSHOP

January 12-14, 2011

Jefferson Laboratory, Harvard University

### ORGANIZERS

Harvard

Randall Kelley  
David Krohn  
Matthew Schwartz

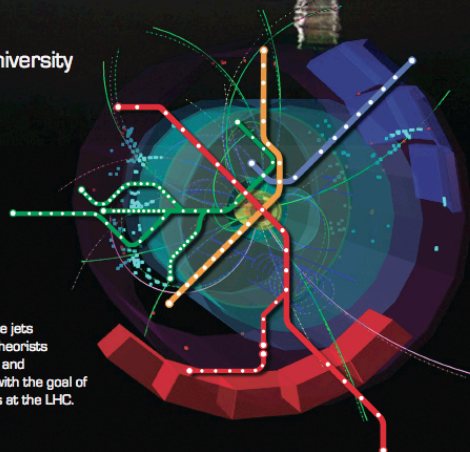
MIT

Christopher Lee  
Keith Rehermann  
Jesse Thaler

Johns Hopkins  
Salvatore Rappoccio

This workshop will focus on improving our ability to use jets in collider physics applications. It will bring together theorists working on both analytic and Monte Carlo jet physics, and experimentalists working to measure jet properties, with the goal of maximizing the physics potential of jet measurements at the LHC.

<http://jets.physics.harvard.edu/>



PRINCETON CENTER FOR THEORETICAL SCIENCE

## Boost 2011

The Boost 2011 conference will be held in May (5/23/11 - 5/27/11) at Princeton University, hosted by the Princeton Center for Theoretical Science. As with prior conferences in the Boost series, the weeklong event will focus on bringing together theorists and experimentalists for in-depth discussions of jets, jet substructure, and jets in more exotic contexts (e.g. lepton jets).

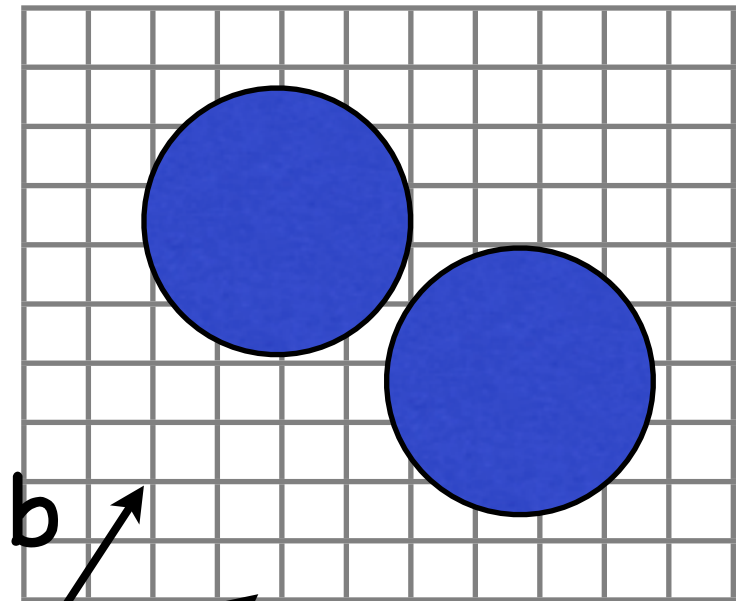
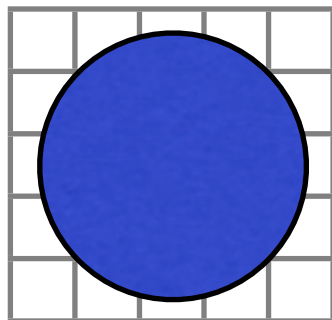
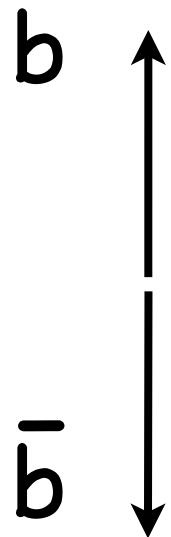
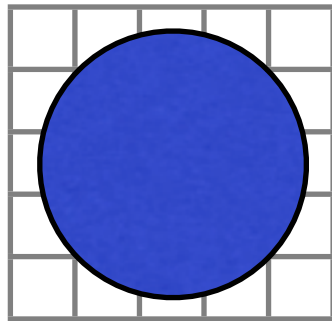
# Jet Substructure

Extract more information out of jets.

Enhance  $S/\sqrt{B}$  for massive objects  
decaying to jets over QCD background.  
(the **boosted** advantage)



# No Boost versus Boost



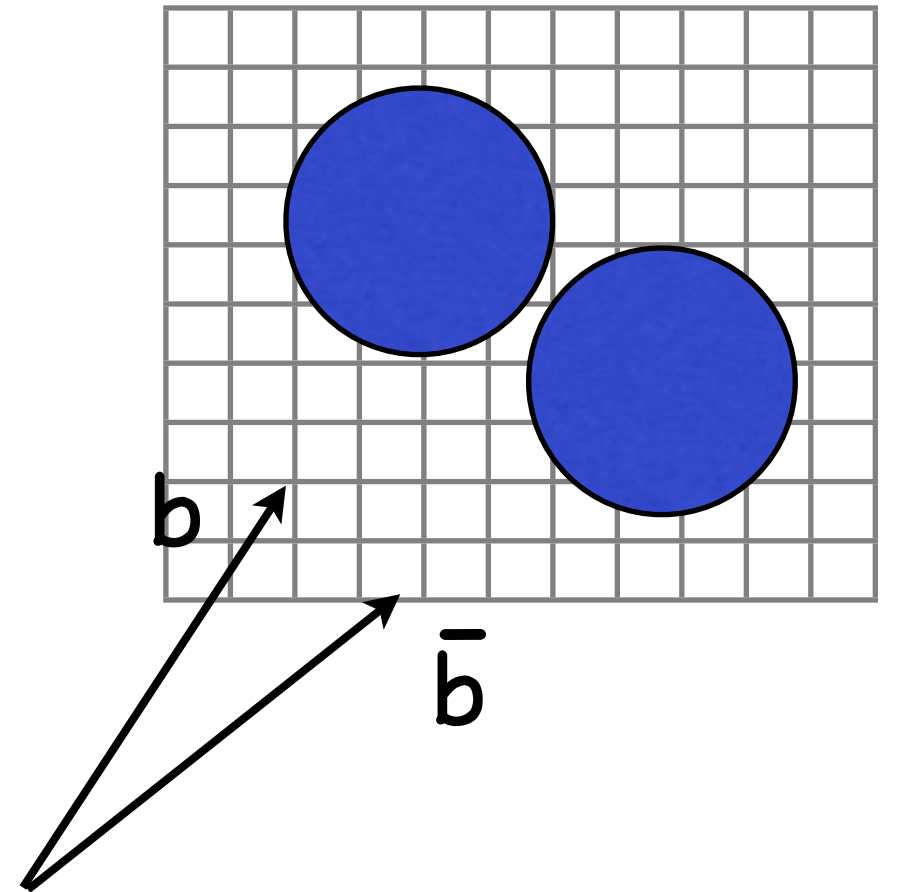
$$\Delta R \approx \frac{2 m_h}{p_T}$$

$$R = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

# Boosted Higgs Decay

Consider  $m_h = 120 \text{ GeV}$ ;  
 $p_T > 200\text{--}300 \text{ GeV}$   
 $\Rightarrow \Delta R \approx 1.2\text{--}0.8$

Jet areas begin to overlap!

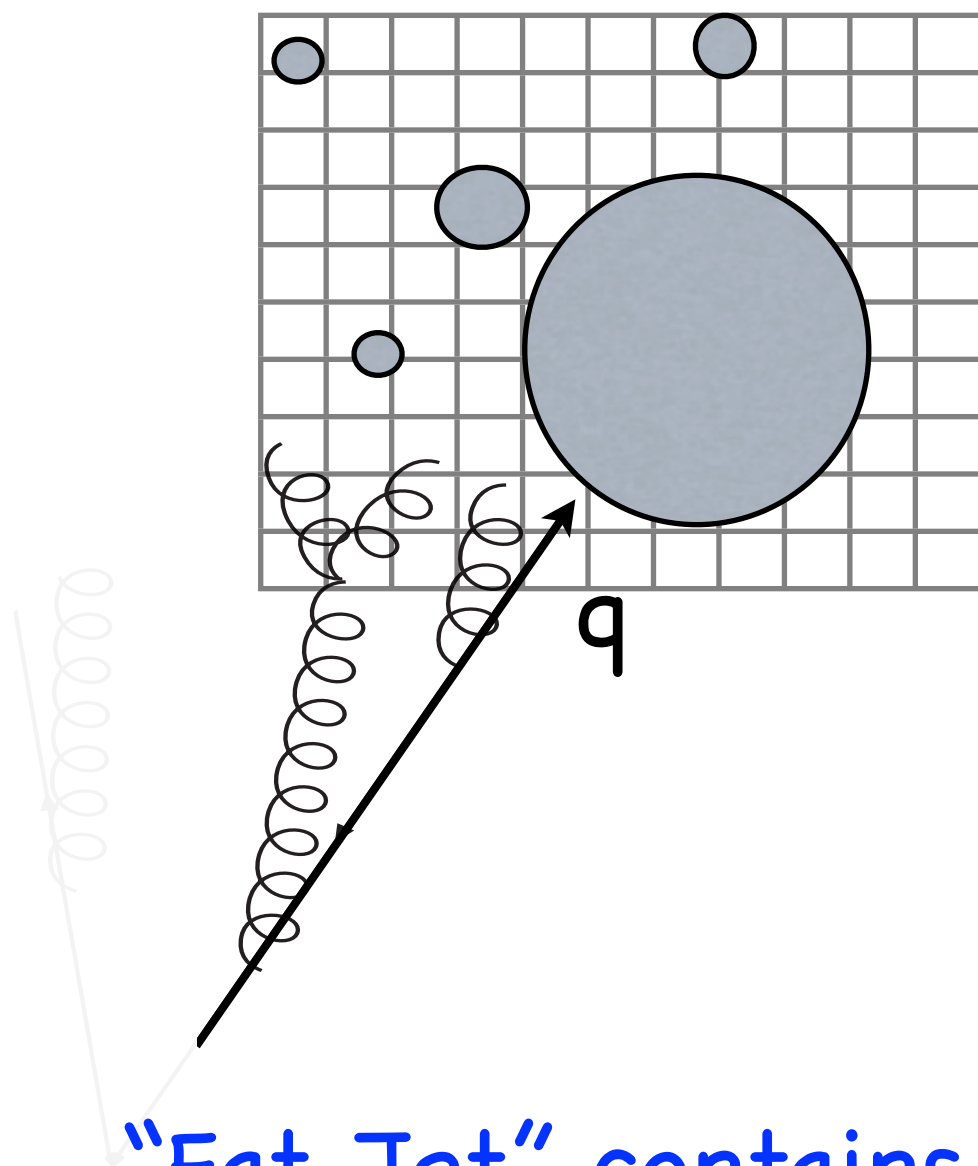


$$\Delta R \approx \frac{2 m_h}{p_T}$$

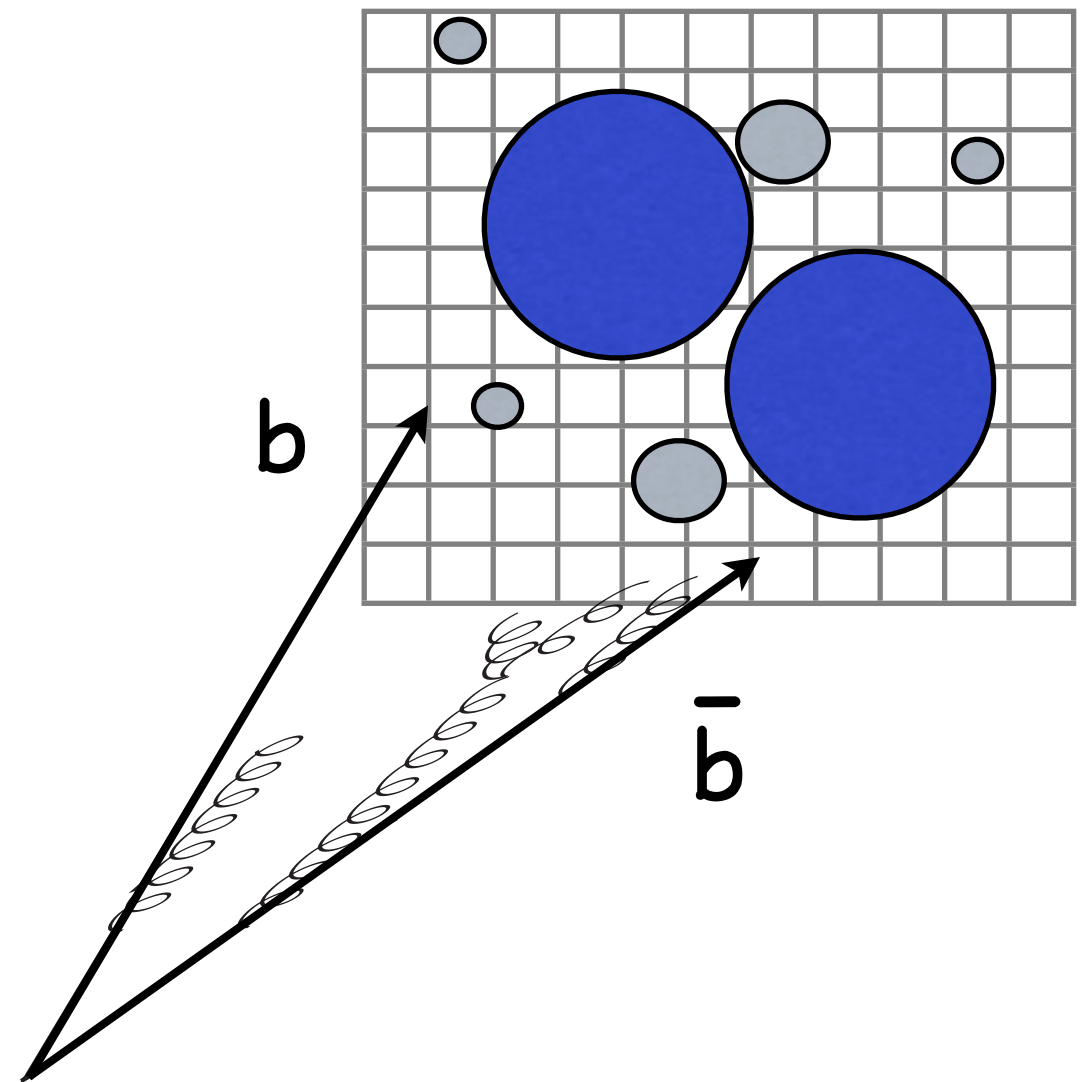
$$R = \sqrt{\Delta y^2 + \Delta \phi^2}$$

# Advantage over Backgrounds

QCD



Boosted Higgs Decay



"Fat Jet" contains multiple hard partons with distinguishable kinematic properties

# Jet Substructure and Filtering

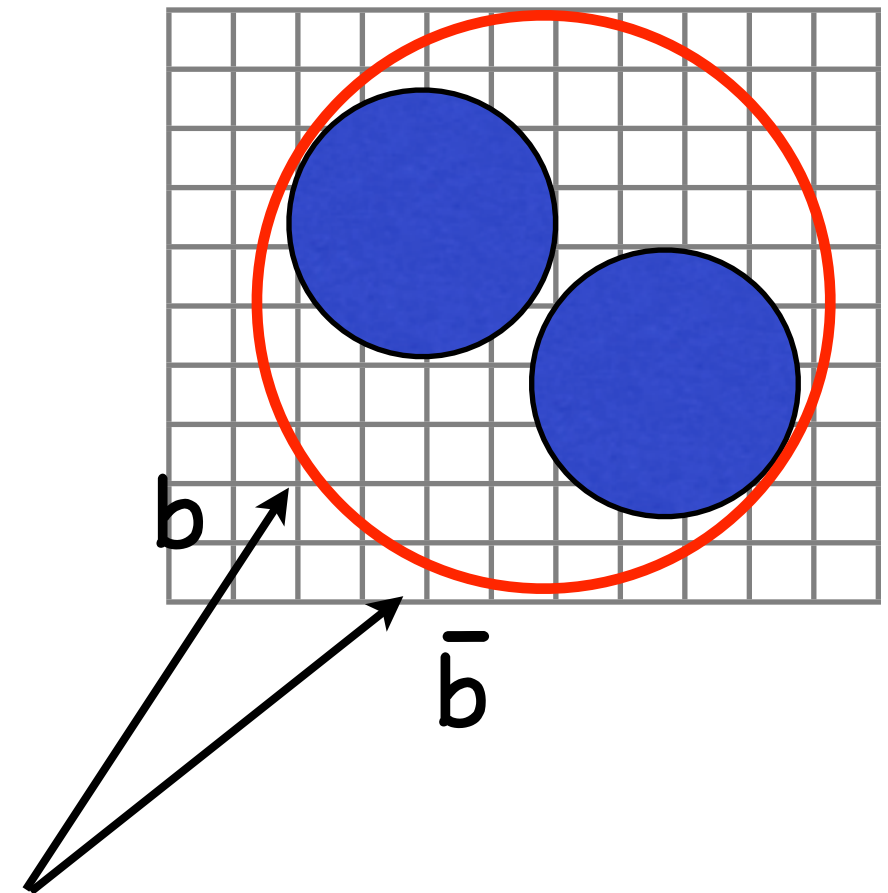
Butterworth, Davison, Rubin, Salam [BDRS: 0802.2470] proposed a set of techniques to find  $h \rightarrow b\bar{b}$  by precisely exploiting the  $S/\sqrt{B}$  advantages of “fat jets”.

The basis of their techniques involves using an iterative jet clustering algorithm (C/A), examining subjet kinematics step-by-step, and finally choosing the “best” subjets from which to form the fat jet mass.

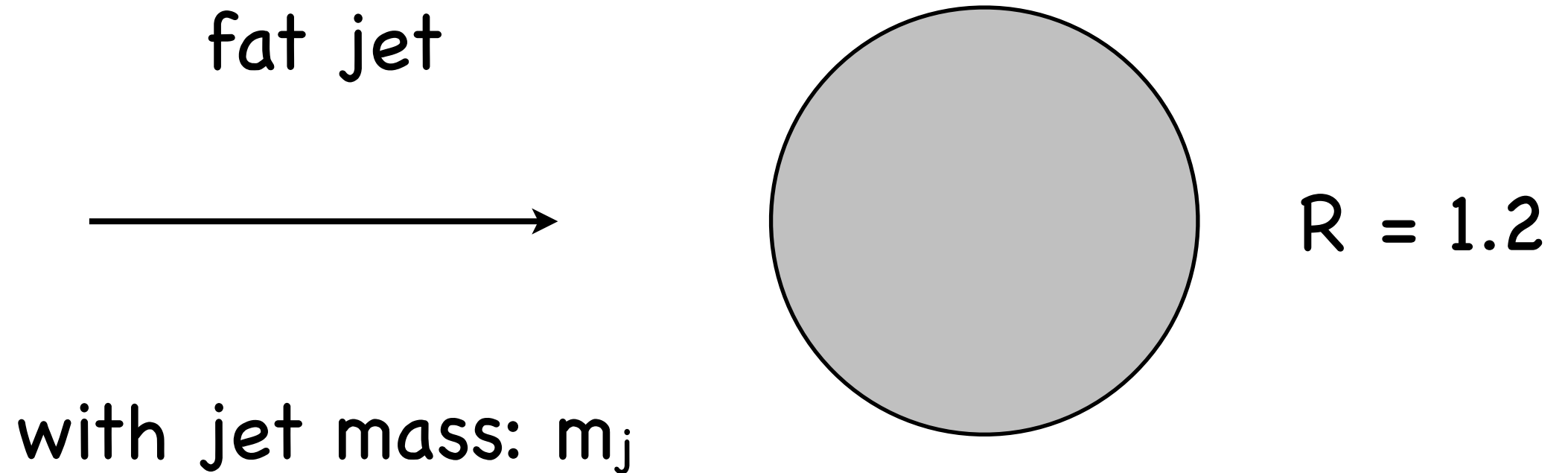
# Fat Jets

$$\text{Given } \Delta R \approx \frac{2 m_h}{p_T} = 1.2 \frac{m_h}{120 \text{ GeV}} \frac{200 \text{ GeV}}{p_T}$$

Let C/A clustering algorithm proceed up to  $R = 1.2$ , to capture both  $b$  jets into one **fat jet**, requiring  $p_T > 200 \text{ GeV}$ .



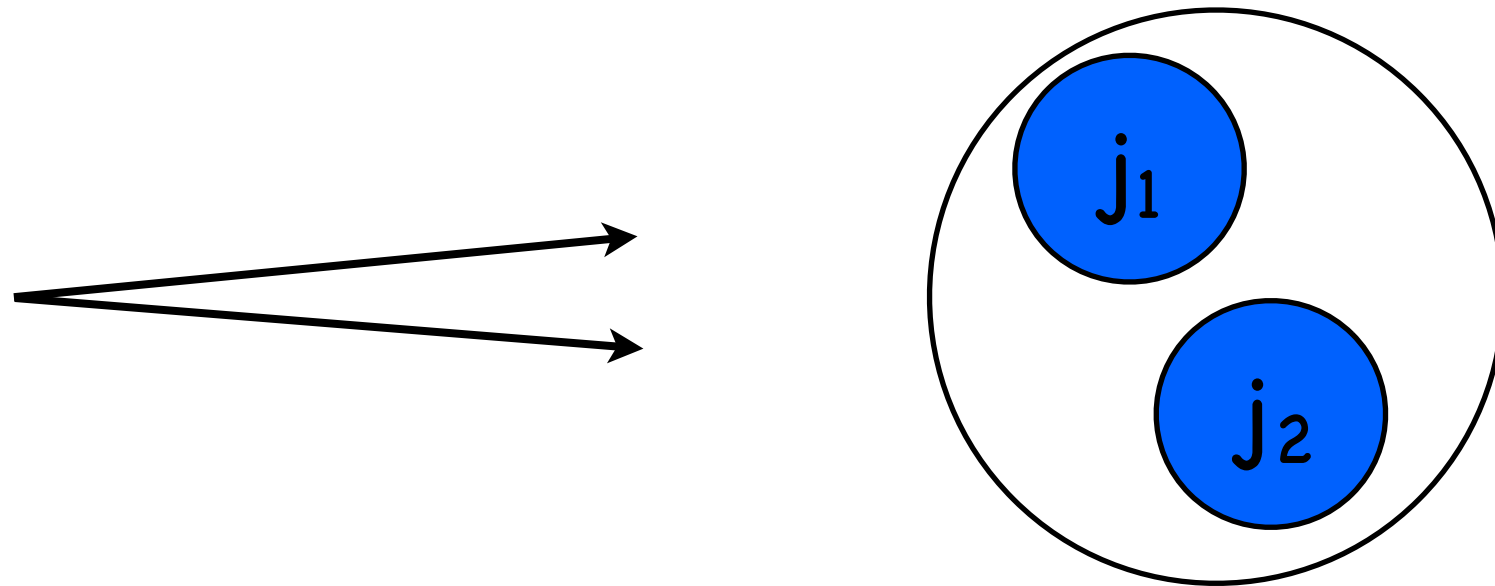
# Jet Decomposition Cartoon





# Jet Decomposition Cartoon

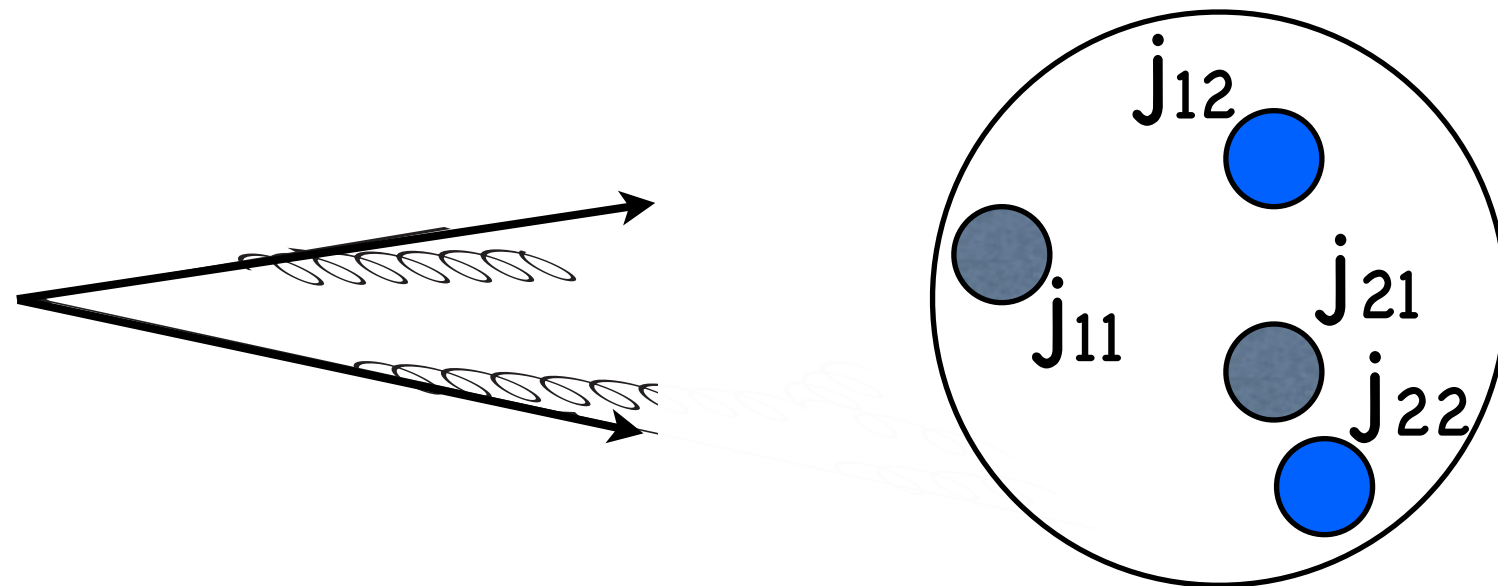
undo clustering



In C/A, this came from two jets with  
jet masses  $m_{j1} > m_{j2}$

# Jet Decomposition Cartoon

repeat unclustering:



four jets with masses:  $m_{j_{11}} > m_{j_{12}}$  ,  $m_{j_{21}} > m_{j_{22}}$

# Higgs Jet Identification

1) check for “mass drop”

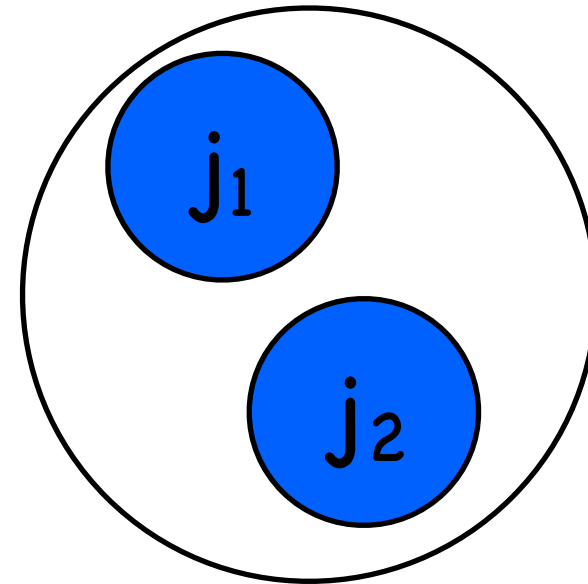
$$m_{j1} < 0.68 m_j?$$

Expect drop for  
heavy particle decay

2) check “asymmetry”

$$y = \frac{\min(p_{tj1}^2, p_{tj2}^2)}{m_j^2} \Delta R_{j1,j2}^2 > y_{\text{cut}}$$
$$y_{\text{cut}} = (0.3)^2$$

Tends to reject soft/colinear  
QCD contamination

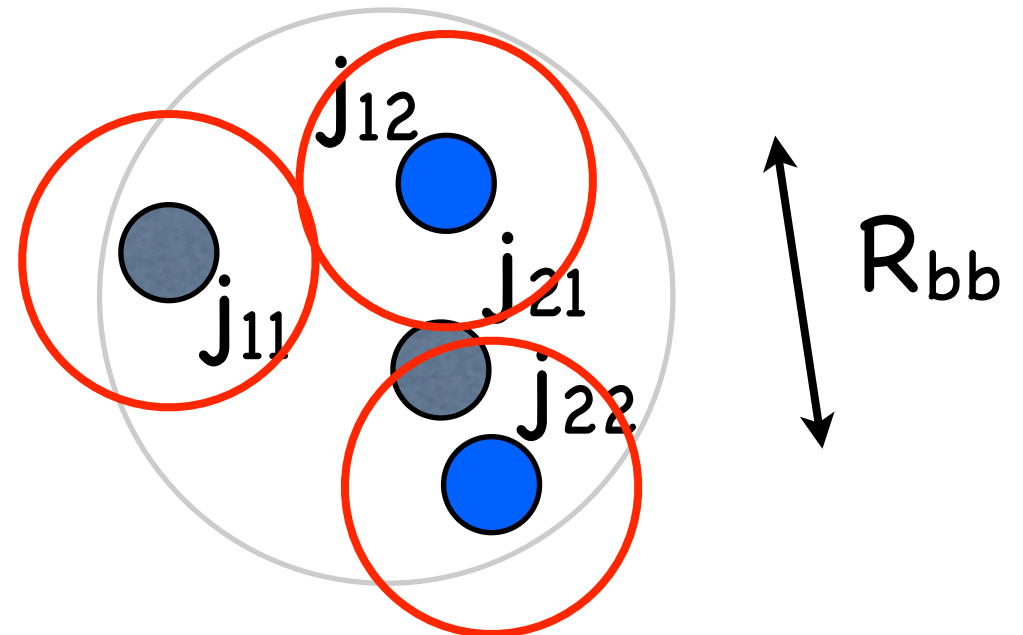


3) require both subjects b-tagged

# Filtering

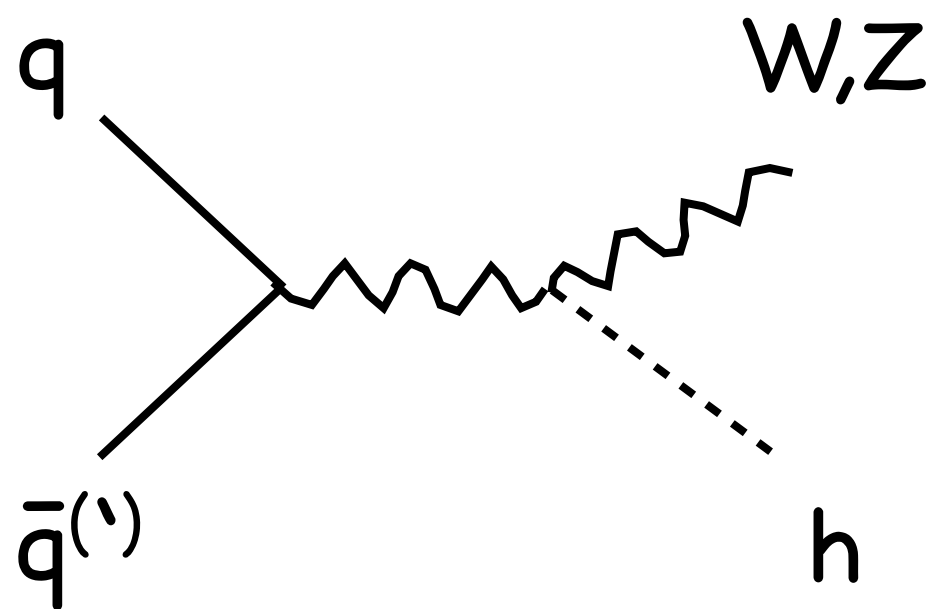
4) **Filter** the subjects to reduce underlying event contamination:

- take 3 highest pT subjects (“third” captures leading parton shower gluon)
- recluster subjects with  $R_{j1,j2,j3} = \min(R_{bb}/2, 0.3)$



Higgs Candidate Mass formed from  
3 highest pT subjects

# Production: Higgs-strahlung

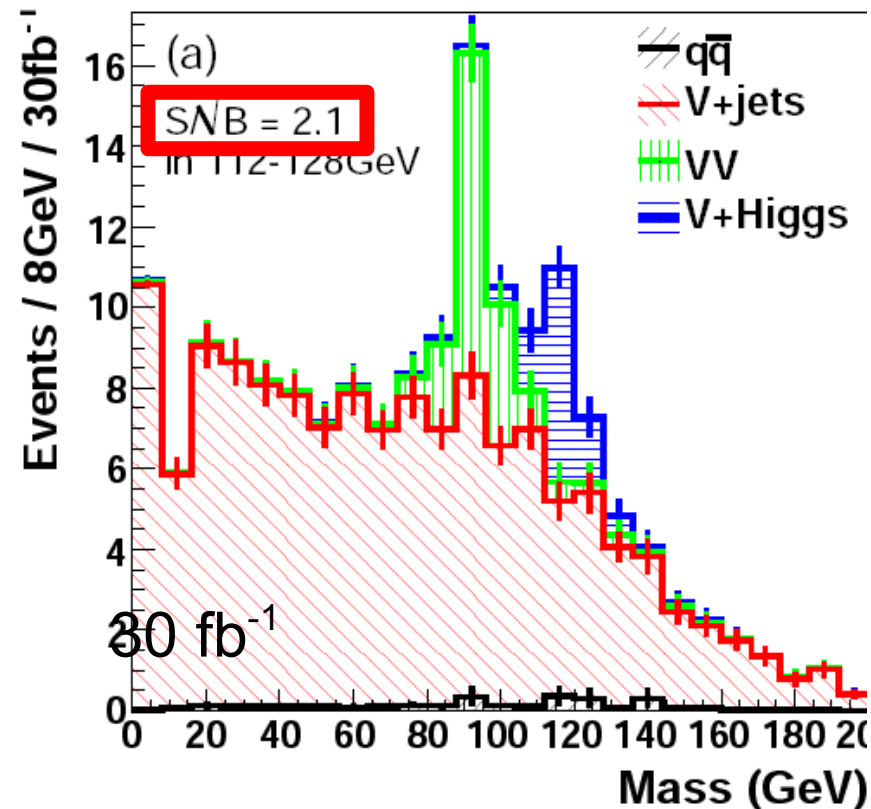


Require Higgs is boosted  
 $p_T(h) > 200 \text{ GeV}$   
(only 5% of  $Zh/Wh$  cross section  
@ 14 TeV)

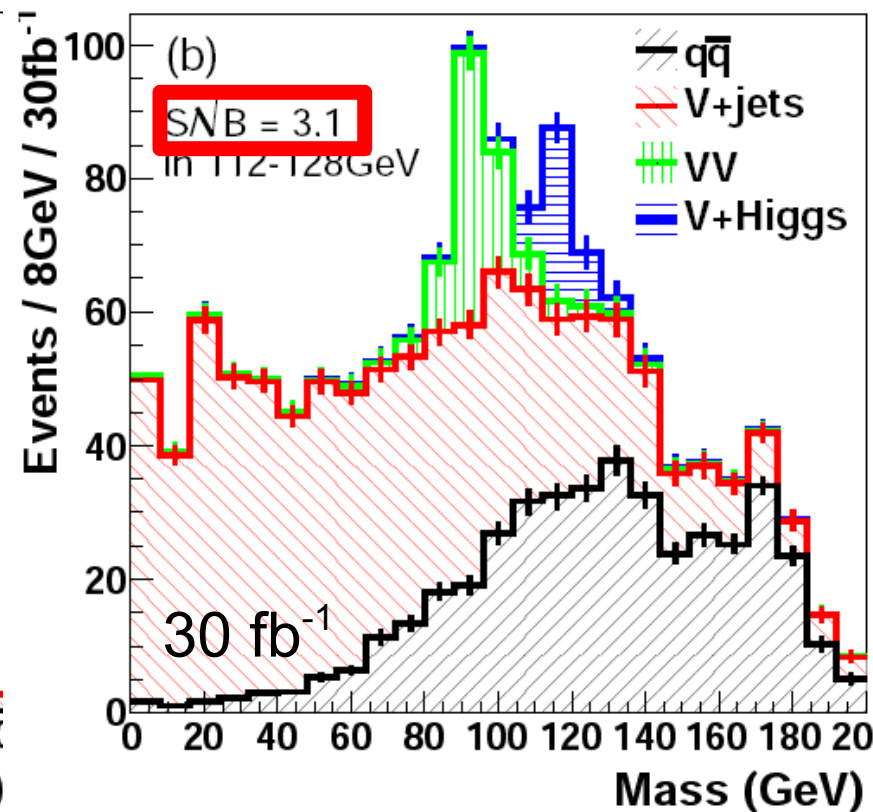
**Leptonic** decay of  $W/Z$  into  
 $llbb, lvbb, vvbb$ .

# BDRS Result

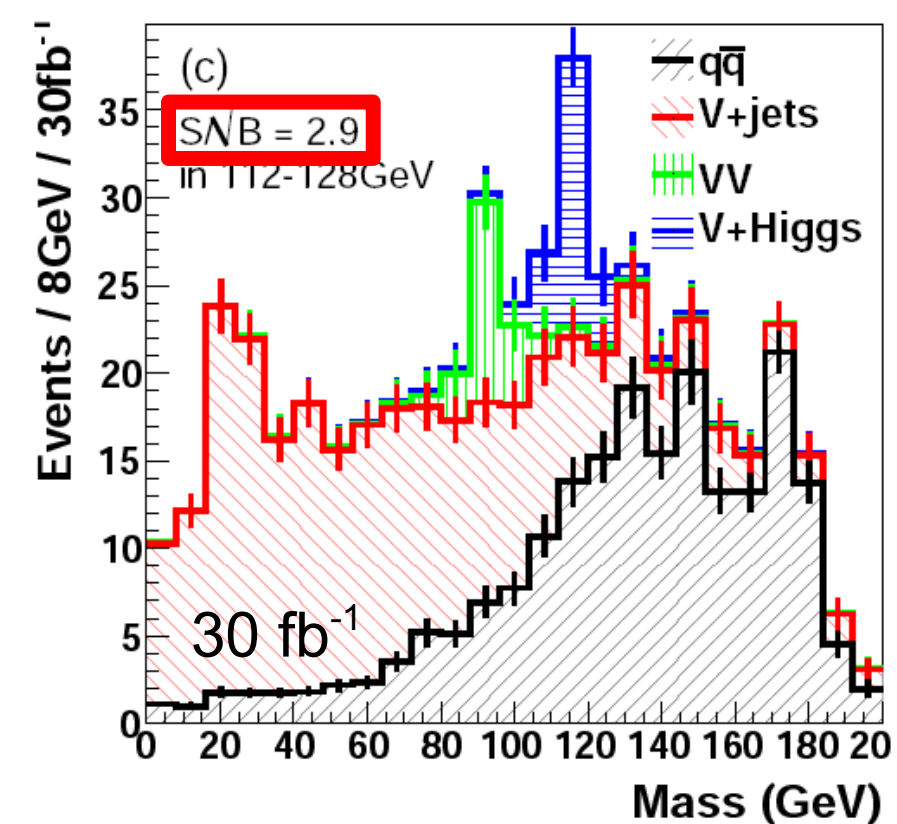
llbb



lvbb



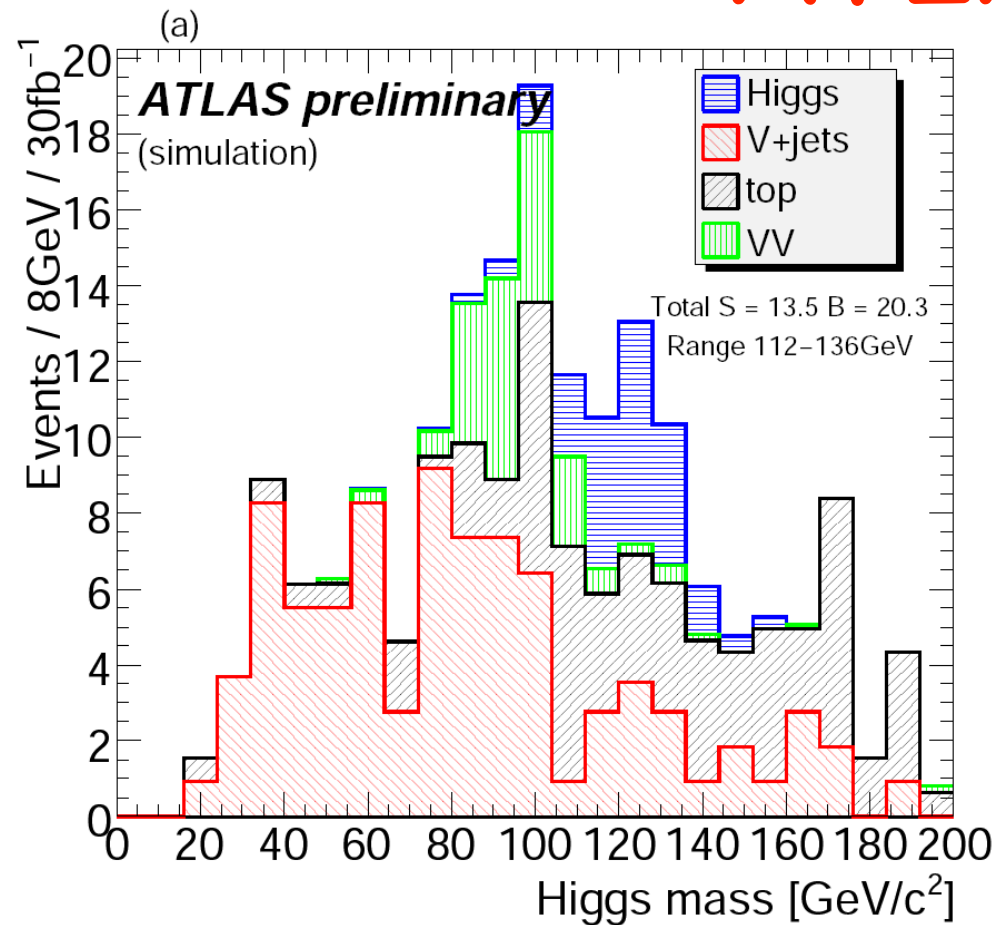
vvbb



- LHC 14 TeV;  $30 \text{ fb}^{-1}$ ;  $m_h = 115 \text{ GeV}$
- HERWIG/JIMMY  
cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- no smearing



# ATLAS Simulation



The WH (W→lv, H→bb) analysis: cut flow  
(main signal and backgrounds samples)

*Loose jet veto and loose b-tagging (to be used as input to likelihood fit):*

	WH(120)	WZ	tt(p <sub>T</sub> <sup>min</sup> )	Wt	W+jets
After filter cuts	1252.8 ± 7.8	9331	1609356	169519	2433885
1 Higgs candidate	569.7 ± 3.0	3509.7 ± 8.0	806175	69375	562030
filtered p <sub>T</sub> > 200 GeV	512.7 ± 3.2	3108 ± 10	709271	60241	413406
Missing E <sub>T</sub> > 30 GeV	362.4 ± 3.2	2183 ± 13	552284	46779	318400
p <sub>T</sub> (W) > 200 GeV	171.0 ± 2.6	1216 ± 12	137946	18524	206331
p <sub>T</sub> (e/μ) > 30 GeV	145.6 ± 2.4	996 ± 11	115053	15724	178004
p <sub>T</sub> (additional μ) < 10 GeV	144.6 ± 2.4	942 ± 11	106836	14992	177542
p <sub>T</sub> (additional e) < 10 GeV	142.9 ± 2.4	885 ± 11	97305	13881	174941
Δφ(W,H) > 2/3 π	142.2 ± 2.4	841 ± 11	84773	12999	167704
no additional b-jets p <sub>T</sub> > 15 GeV	130.6 ± 2.3	790 ± 10	30605	7805	160608
add. jets on W side p <sub>T</sub> < 60 GeV	115.7 ± 2.2	637.2 ± 9.5	19422	5870	121437
add. jets on H side p <sub>T</sub> < 60 GeV	102.7 ± 2.1	525.6 ± 8.8	13841	4370	94055
one subjet b-tagged	91.4 ± 2.0	126.1 ± 4.5	8638	2421	6964
both subsets b-tagged	45.6 ± 1.4	43.7 ± 2.7	576	161.4 ± 7.0	266
loose fit cuts	45.4 ± 1.4	43.0 ± 2.7	565	156.3 ± 6.9	257

*Tight jet veto and tight b-tagging at ε<sub>b</sub> ~ 63 % and c(l) = 0.2 (for counting based analysis)*

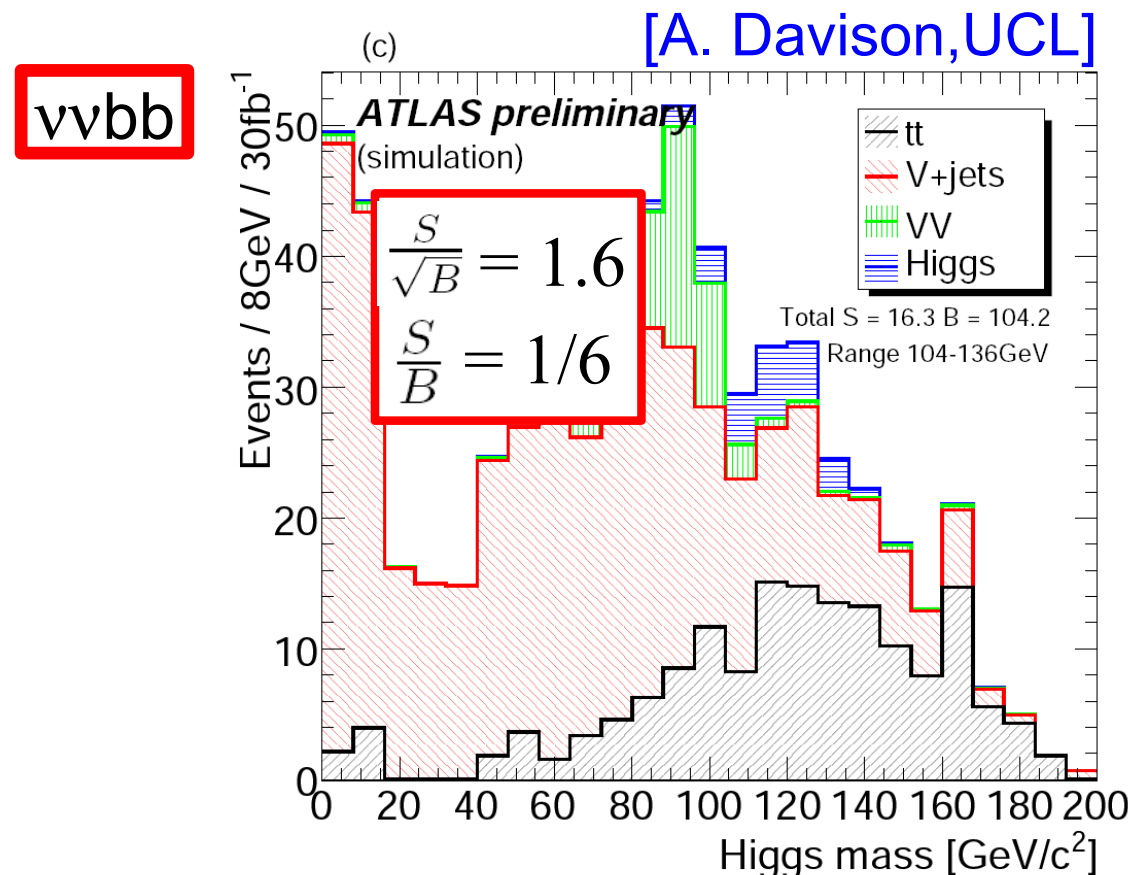
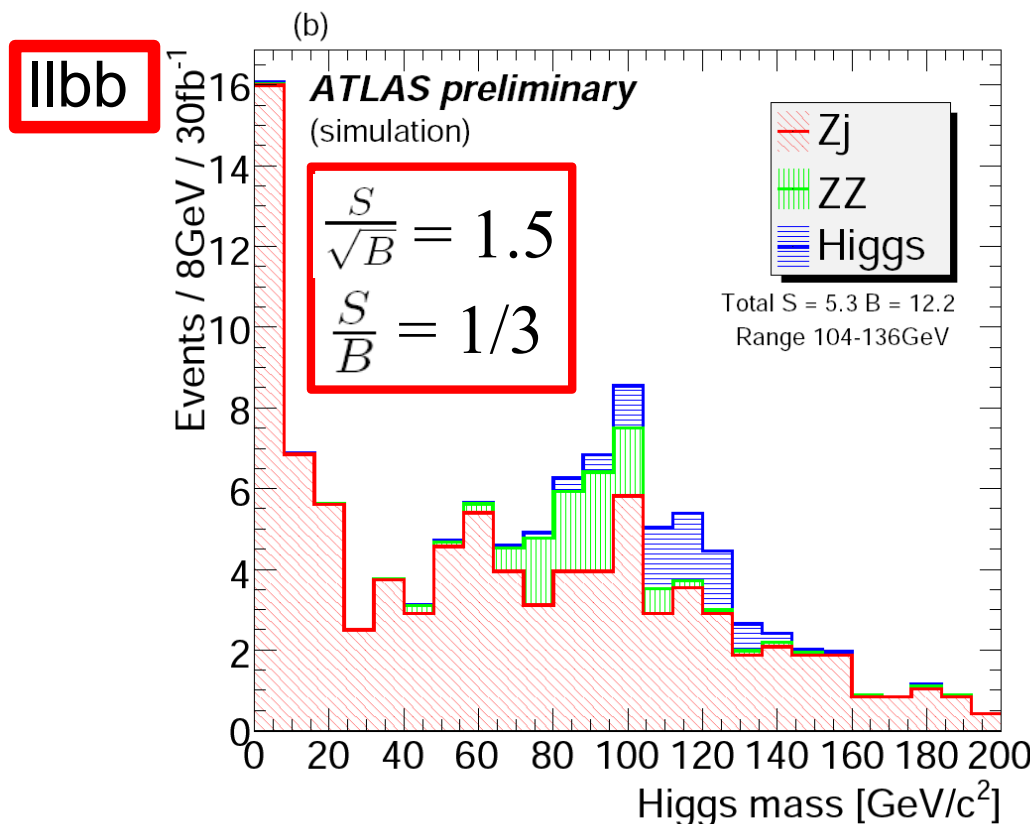
	WH(120)	WZ	tt(p <sub>T</sub> <sup>min</sup> )	Wt	W+jets
add. jets on W side p <sub>T</sub> < 20 GeV	83.2 ± 1.9	461.3 ± 8.3	7227	3343	86087
add. jets on H side p <sub>T</sub> < 20 GeV	55.8 ± 1.6	275.6 ± 6.6	1895	1142	48229
one subjet b-tagged	46.4 ± 1.5	49.8 ± 2.9	986	498 ± 12	1825
both subsets b-tagged	19.51 ± 0.96	16.5 ± 1.7	38.9 ± 4.9	18.2 ± 2.4	87.3 ± 9.0
112 GeV < mass(H) < 136 GeV	13.25 ± 0.79	1.18 ± 0.45	5.6 ± 1.9	4.2 ± 1.1	8.3 ± 2.8

Signal events (m<sub>H</sub> ~ 120 GeV): ~13.5

Background events: ~20.3

$$\frac{S}{\sqrt{B}} = 3.0 \pm 0.3$$

Giacinto Piacquadio



[A. Davison, UCL]

# Strongly Motivating!

- background uncertainty

$\sigma_t$	$\sigma_w$	$\sigma_z$	Significance
Perfect	Perfect	Perfect	3.7
5%	5%	5%	3.5
10%	10%	10%	3.2
15%	15%	15%	3.0
20%	20%	20%	2.8

Channel	signal	$t_i$	$w_i$	$z_i$	$S/\sqrt{B}$
$llb\bar{b}$	5.34	0.98	0.0	11.2	1.5
$l\nu b\bar{b}$	13.5	7.02	12.5	0.78	3.0
$\nu\nu b\bar{b}$	16.3	45.2	27.4	31.6	1.6
Combined					3.7

♦ **10/15 %** uncertainty considered as realistic:

♦ Median discovery significance:  
**3.0-3.2**

- b-tagging efficiency (better for subjects!)
- underlying event
- pile-up; at  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  mass resolution of Higgs degraded with C/A; more elaborate techniques?

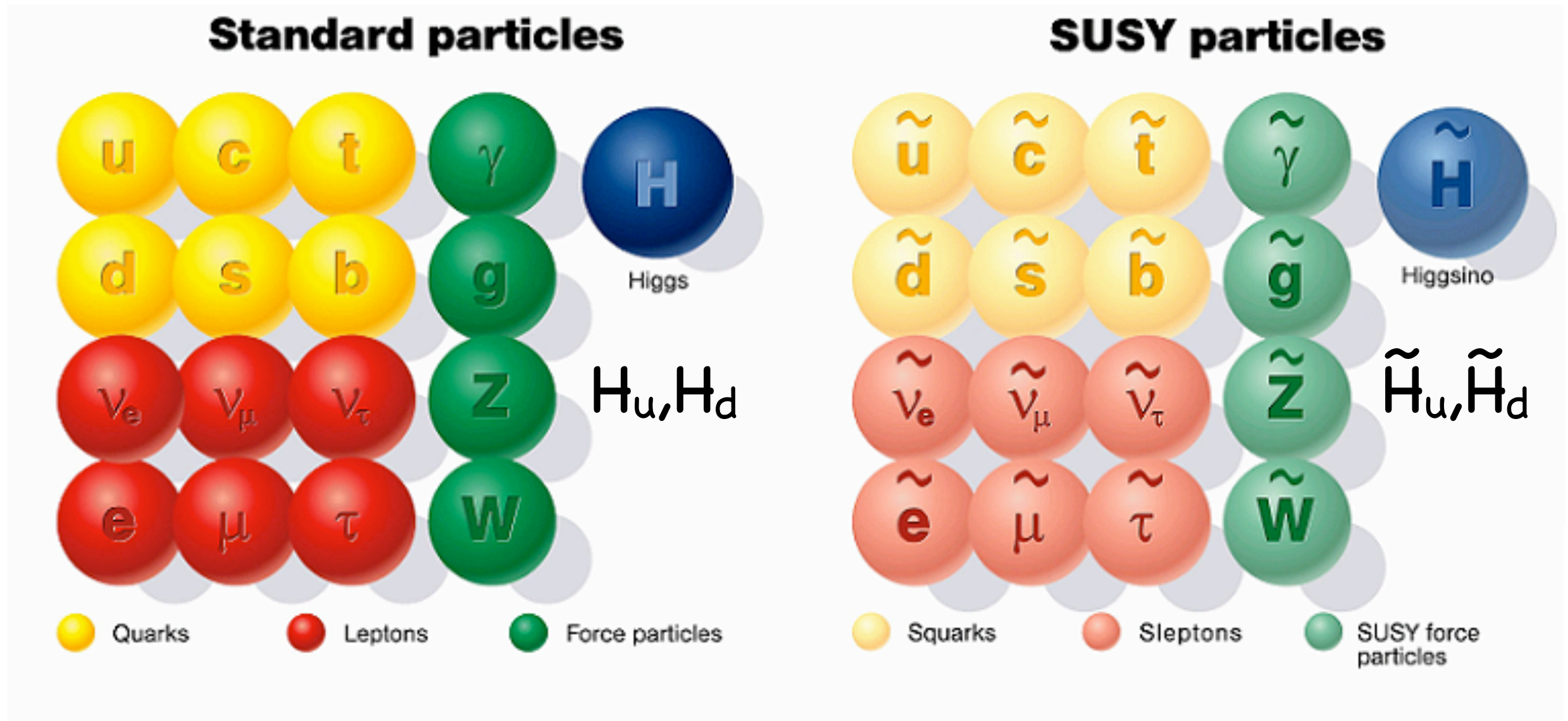
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# Weak Scale Supersymmetry



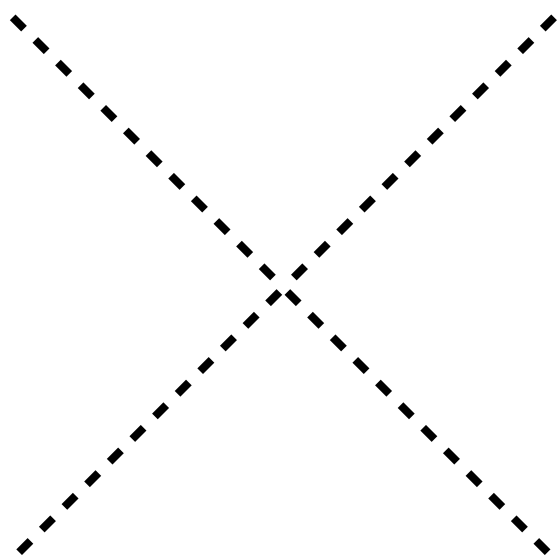
“Minimal Supersymmetric Standard Model (MSSM)”

# Higgs Sector of MSSM

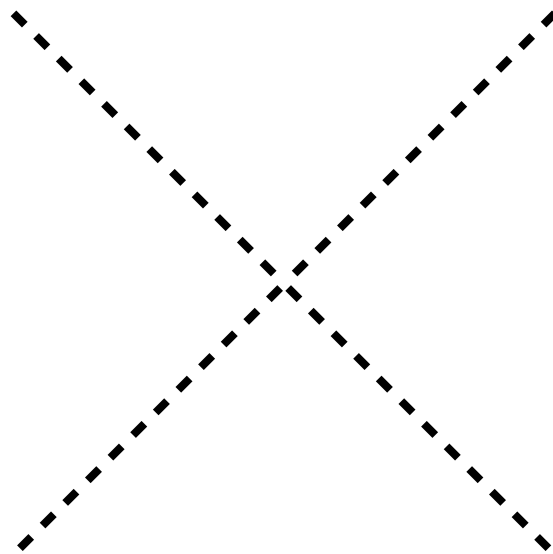
quartic coupling  
 $\lambda$

determined!  
 $g^2 + (g')^2$

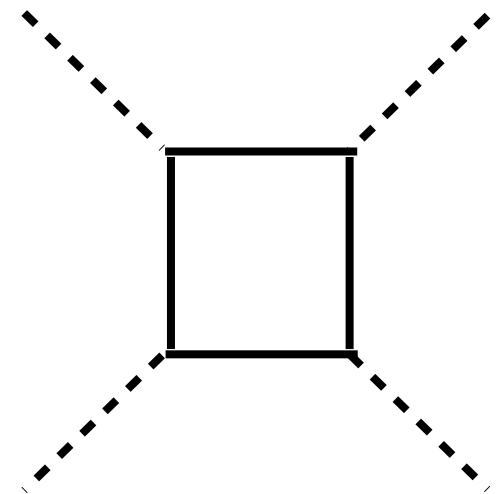
up to radiative  
corrections



=



+



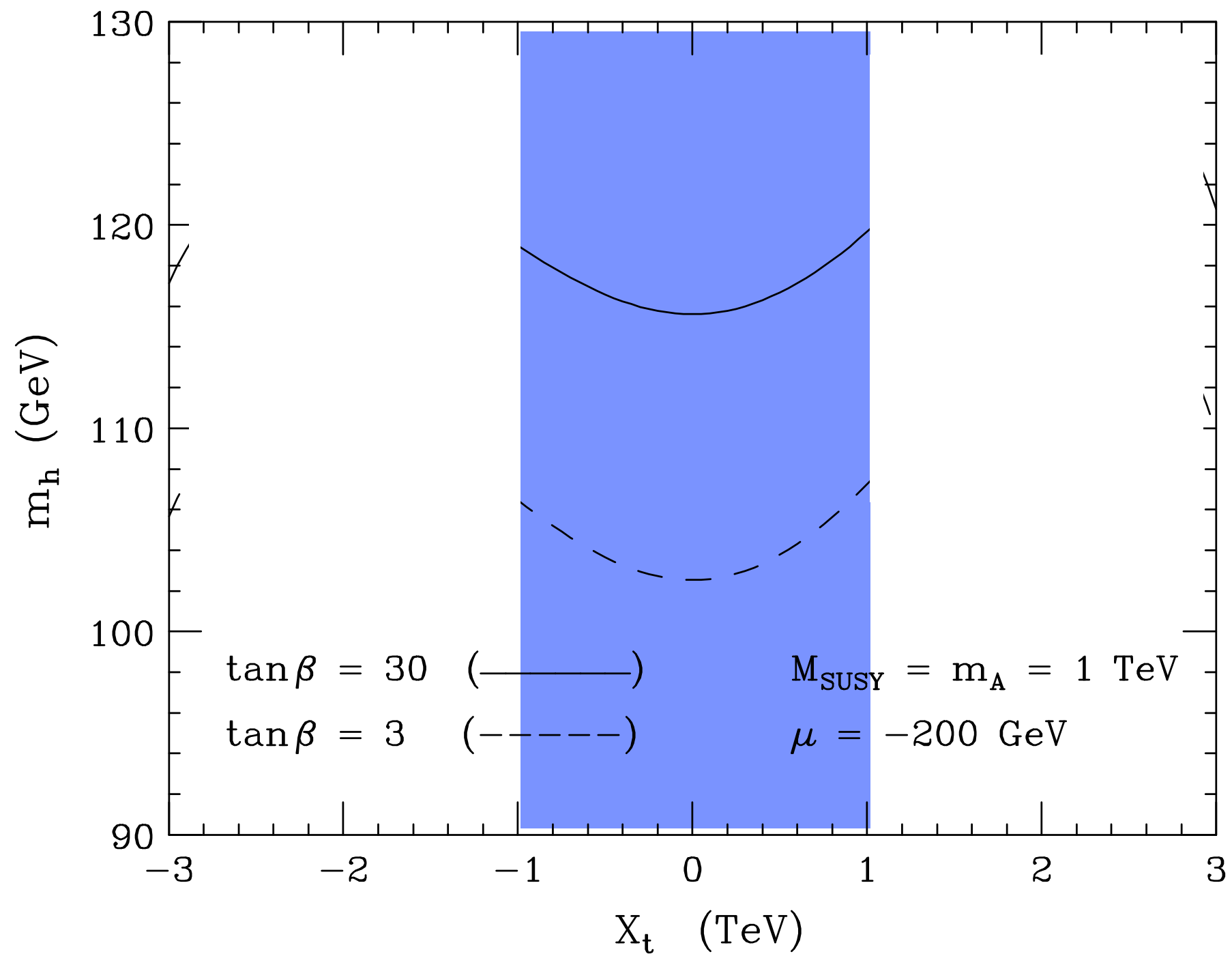
+ ...

$$m_h^2 = M_Z^2 \left( \frac{\tan^2 \beta - 1}{\tan^2 \beta + 1} \right)^2 +$$

$$y_t^4 \log m_{st}/m_t$$

(schematic)

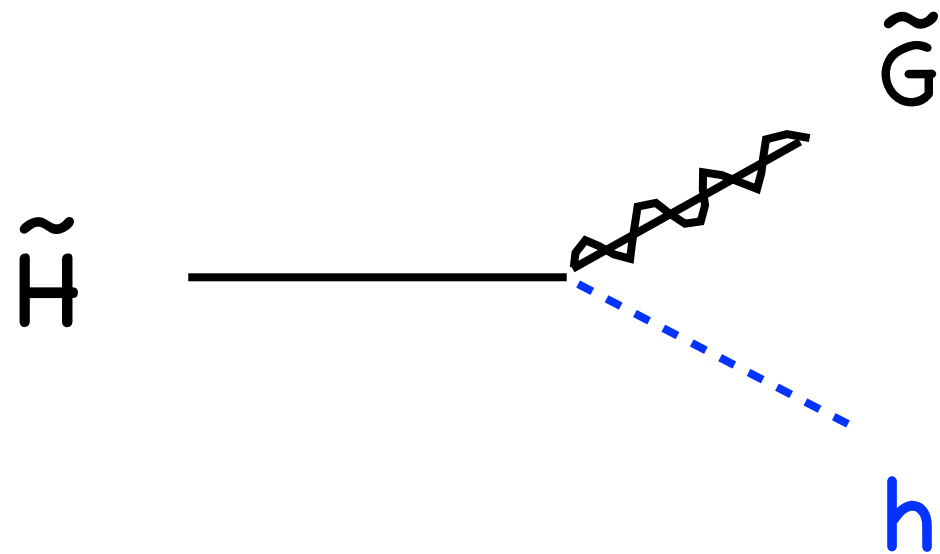
# h is light





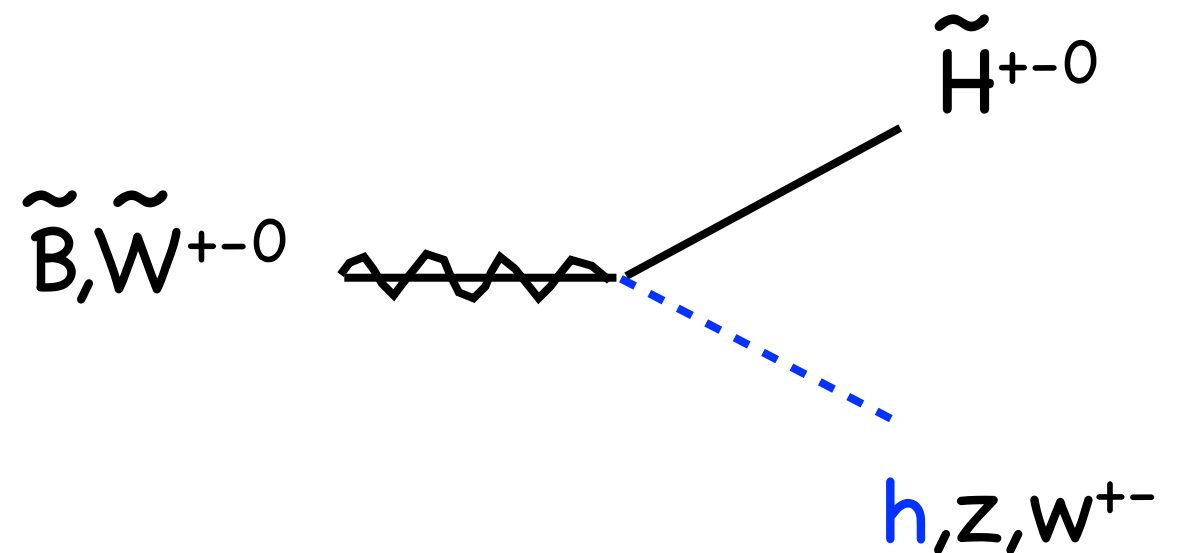
# Superpartner Decay to Higgs

SUSY with a gravitino LSP and Higgsino NLSP:



BR up to 50%

SUSY with a Higgsino LSP:



BR  $\approx$  25%

Kinematical requirement

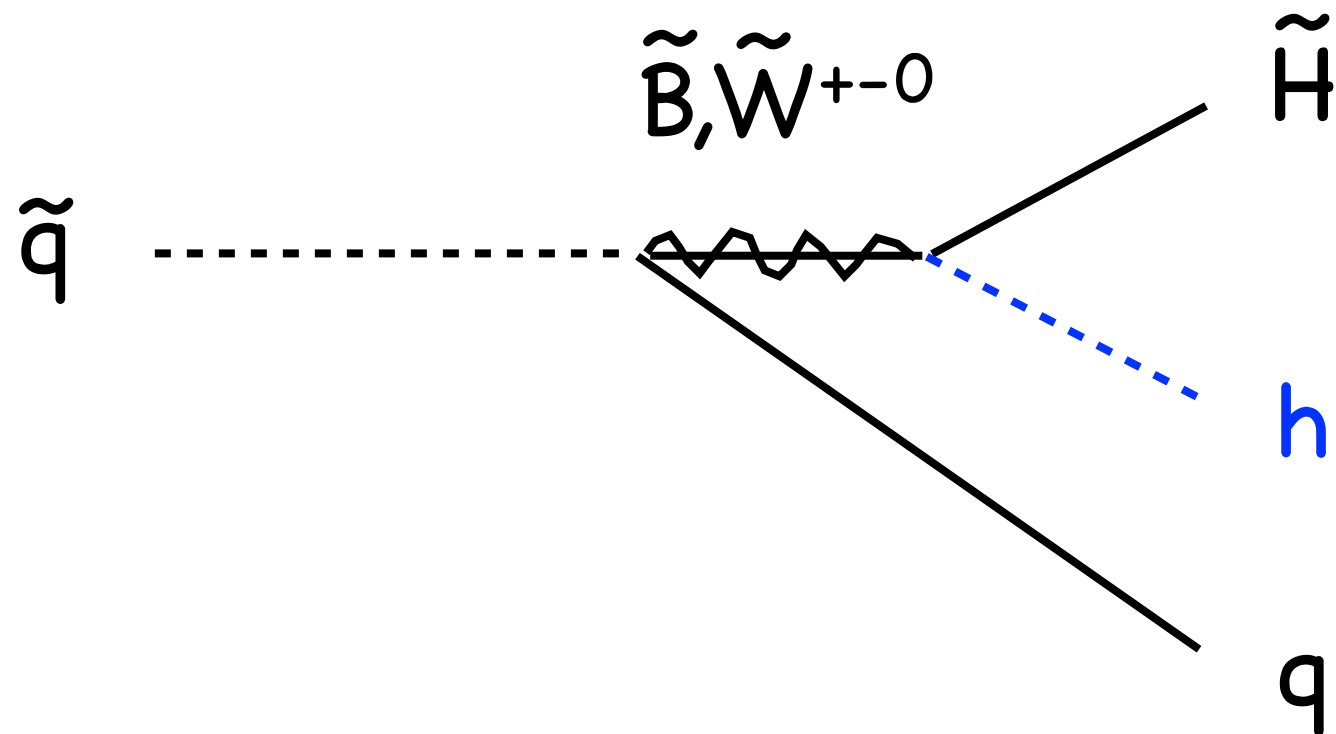
$$\begin{aligned} \mu &> m_{\tilde{G}} + m_h \\ &> 120 \text{ GeV} \end{aligned}$$

$$\begin{aligned} m_{\text{Wino}} &> \mu + m_h \\ &> 100 + 120 = 220 \text{ GeV} \end{aligned}$$



# Squark Production to Gauginos

(which then decay to Higgs)



typical  $\sigma(\text{squarks})_{14 \text{ TeV}} \approx \text{several pb!!}$

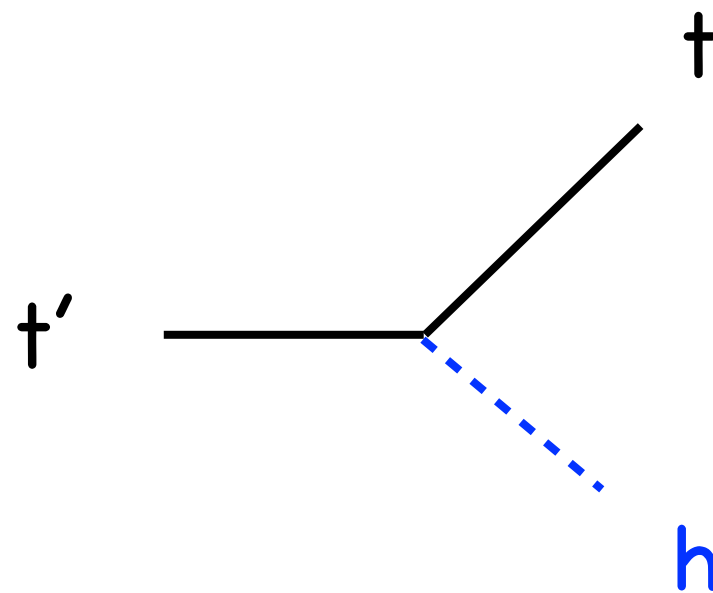
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# Top Partners

little Higgs models, top color, ...

Vector-like pair of quarks  $T(3,1,2/3)$ ,  $\bar{T}(\bar{3},1,-2/3)$



“Goldstone region”  
for  $m(t') \gg m(t)$   
 $\approx 25\%$  of time decay  
to  $h$   
 $\approx 75\%$  of time to  
longitudinal  $W/Z$

Kinematical requirement

$$\begin{aligned} m_{t'} &> m_t + m_h \\ &> 175 + 120 = 295 \text{ GeV} \end{aligned}$$

# Key Advantages of New Physics Source

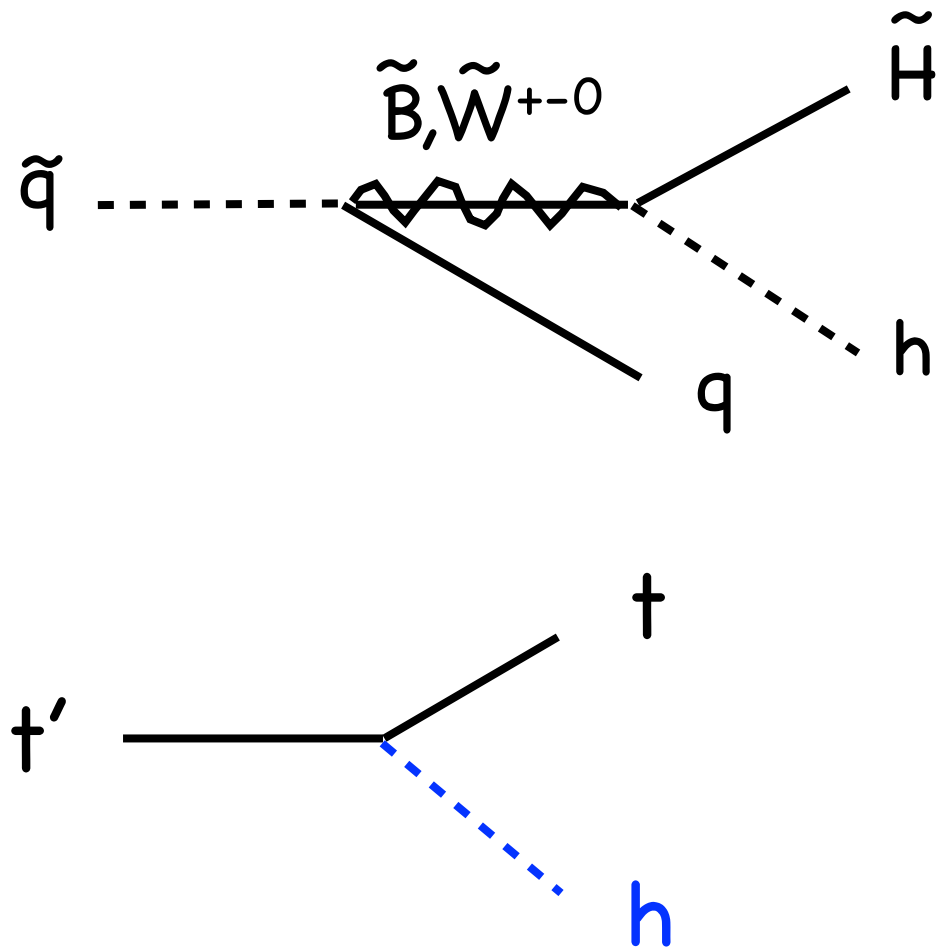
- Production source can be **QCD** (enhanced!)
- Cascade decays from heavy new particles leads to **significant boost** for a **large fraction** of events
- In **MSSM**, Higgs is always light

(in other models, lighter Higgs  
consistent with EW precision data)

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# New Physics Production -- Busy Events!



New physics events tend to be “busy” with a lot of hadronic activity from squark/gluino/top-partner decay and associated parton showers.

Can have extra hard subjects in “fat jet” cone!

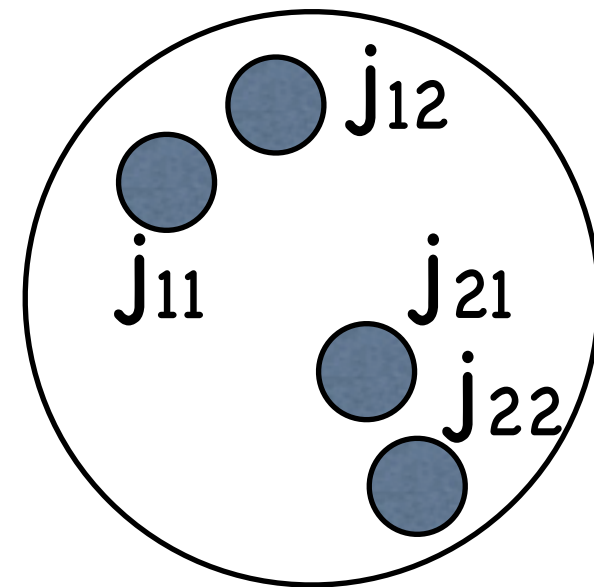
Similar problem also with  $t, t\text{-bar}, h$ !

# Our New Step

## Search Jet Daughters for Maximal “Similarity”

At each stage of unclustering,  
calculate “similarity”:

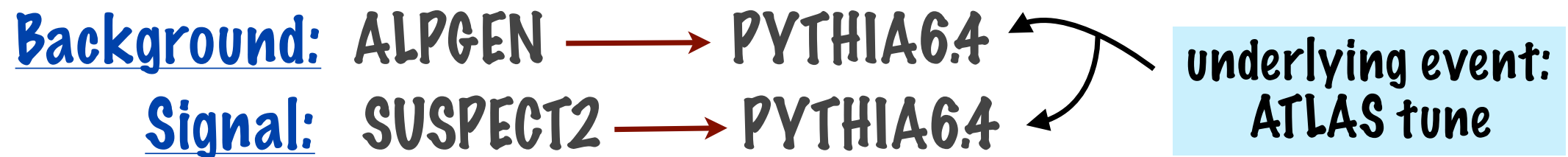
$$S_i = \frac{\min(p_{t_{j_1}}^2, p_{t_{j_2}}^2)}{(p_{t_{j_1}} + p_{t_{j_2}})^2} \Delta R_{j_1 j_2}$$



Choose 3 highest pT jets from stage which maximizes “S”

This helps improve the efficiency of finding the Higgs by  
 $\approx 10\text{--}20\%$  by not rejecting fat jets with stray b-tagged jet.

# Simulation details...



- All final-state hadrons grouped into cells of size  $(\Delta\eta \times \Delta\phi) = (0.1 \times 0.1)$
- Each cell is rescaled to be massless  
this models detector response (Thaler, Wang '08)

jet gymnastics performed using **FastJet** ([hep-ph/0512210](https://arxiv.org/abs/hep-ph/0512210))

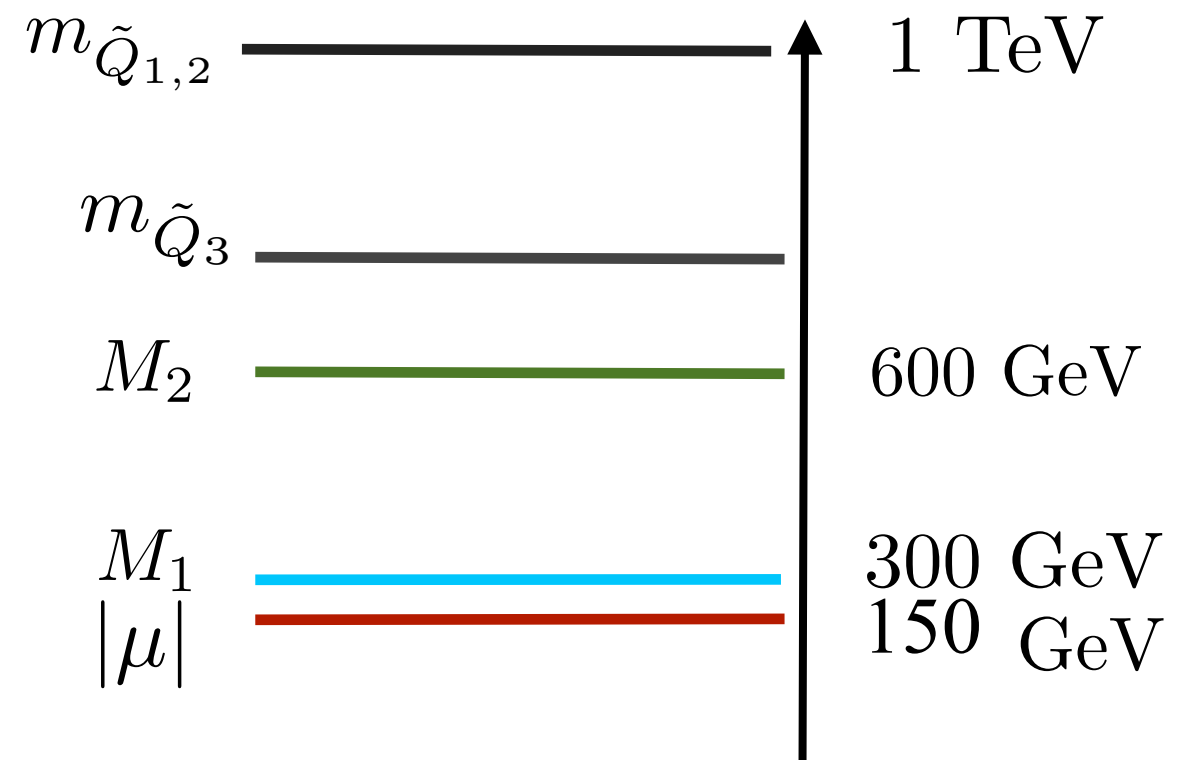
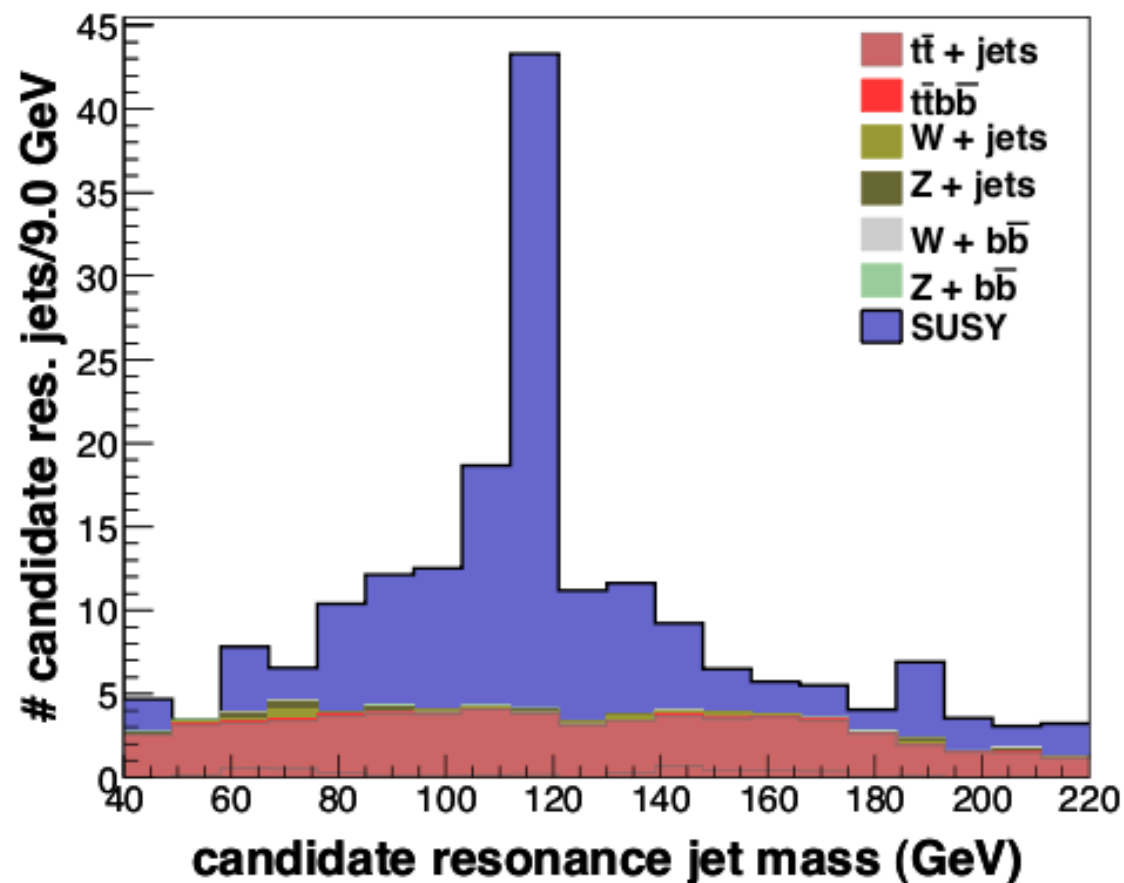
b-tagging: 60% efficiency, 2% fake rate

jet-photon fake rate: .1%



# Example 1: MSSM with Higgsino LSP

10 fb<sup>-1</sup> @ 14 TeV



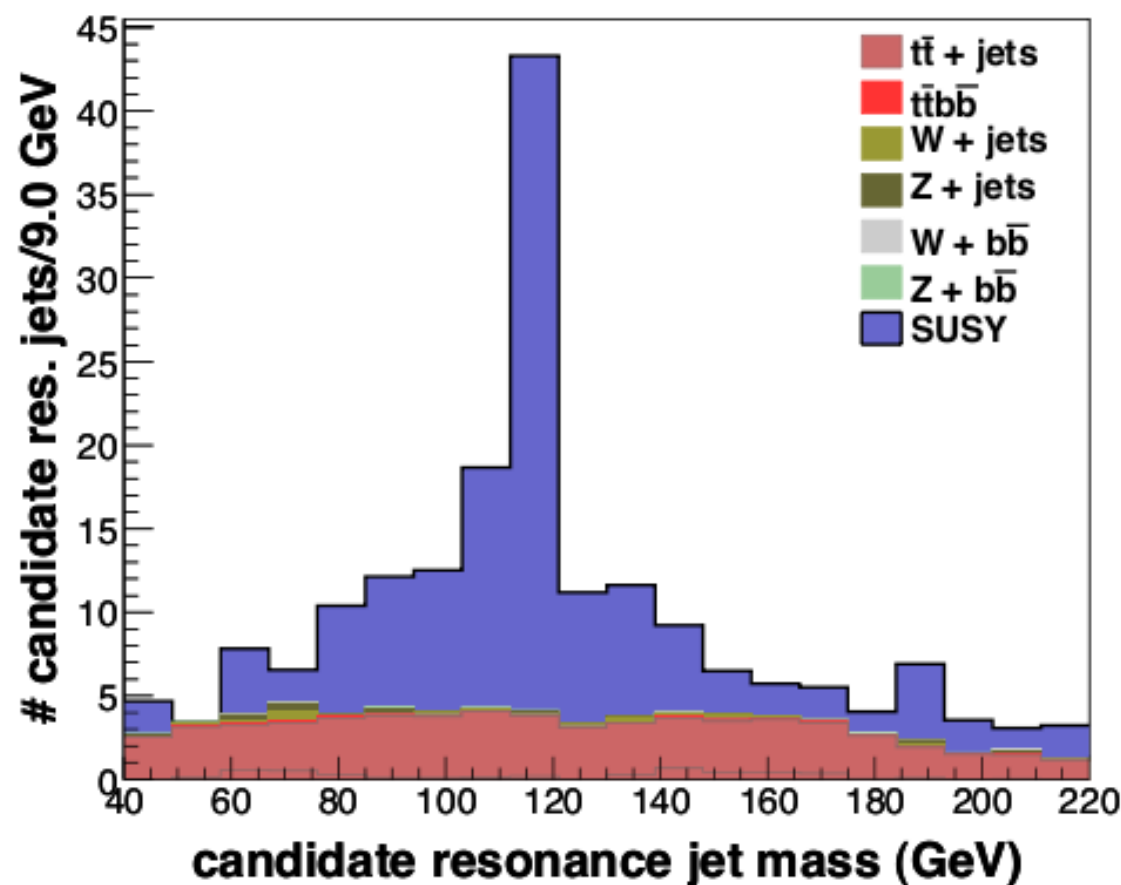
GK, Martin, Roy, Spannowsky; 1006.1656

MET > 300 GeV, H<sub>T</sub> > 1 TeV, 3+ jets,  
no lepton, + 1 "tagged" Higgs

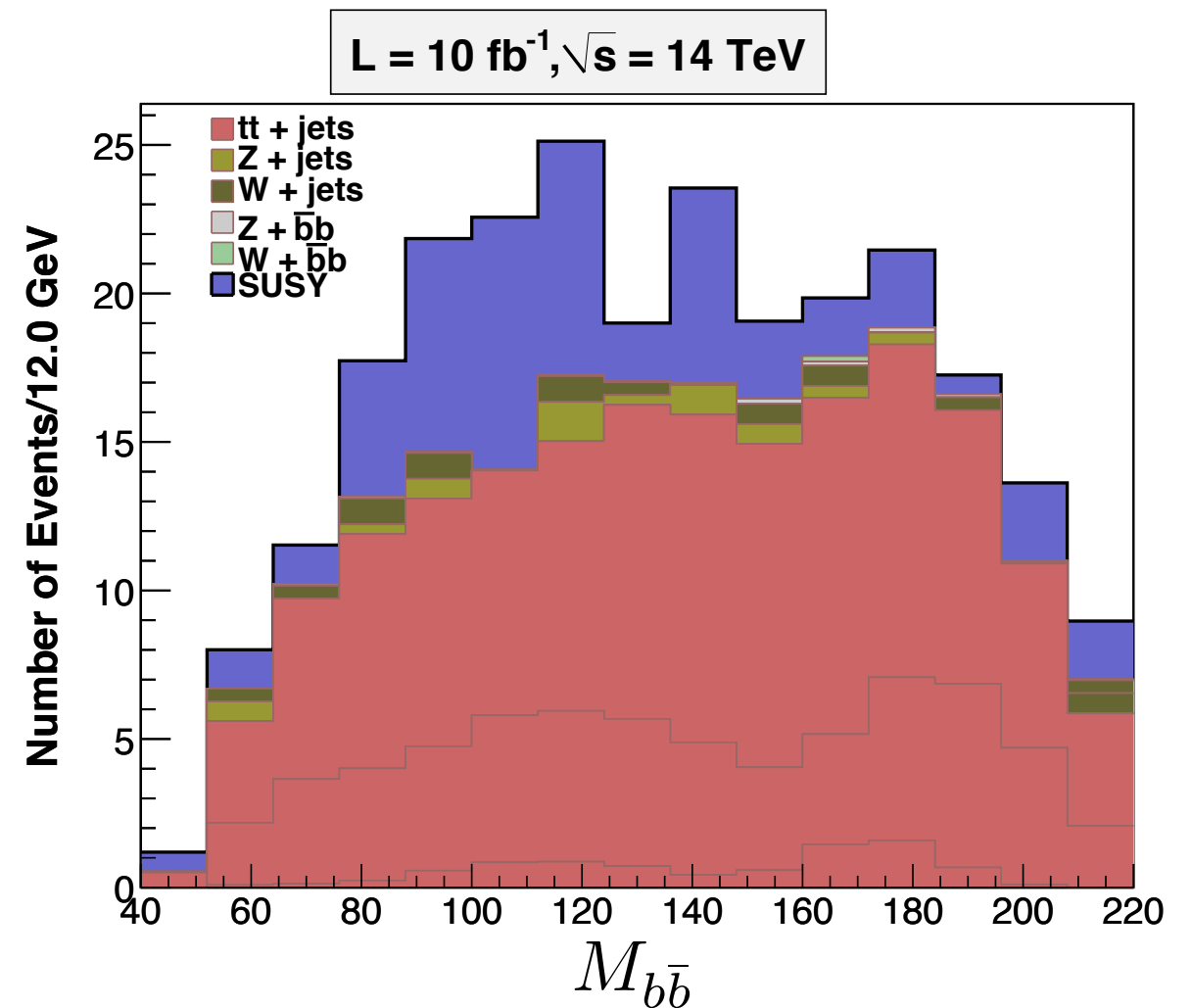
$$BR(\tilde{u}_L, \tilde{d}_L \rightarrow h + X) \sim 23\%$$
$$BR(\tilde{u}_R, \tilde{d}_R \rightarrow h + X) \sim 16\%$$

# "What good is that fancy substructure?"

Comparison\*: with substructure analysis vs. with PGS



$H_T > 1 \text{ TeV}, \cancel{E}_T > 300 \text{ GeV}$   
 $3^+$  high- $p_T$  jets, no leptons  
 1 candidate Higgs



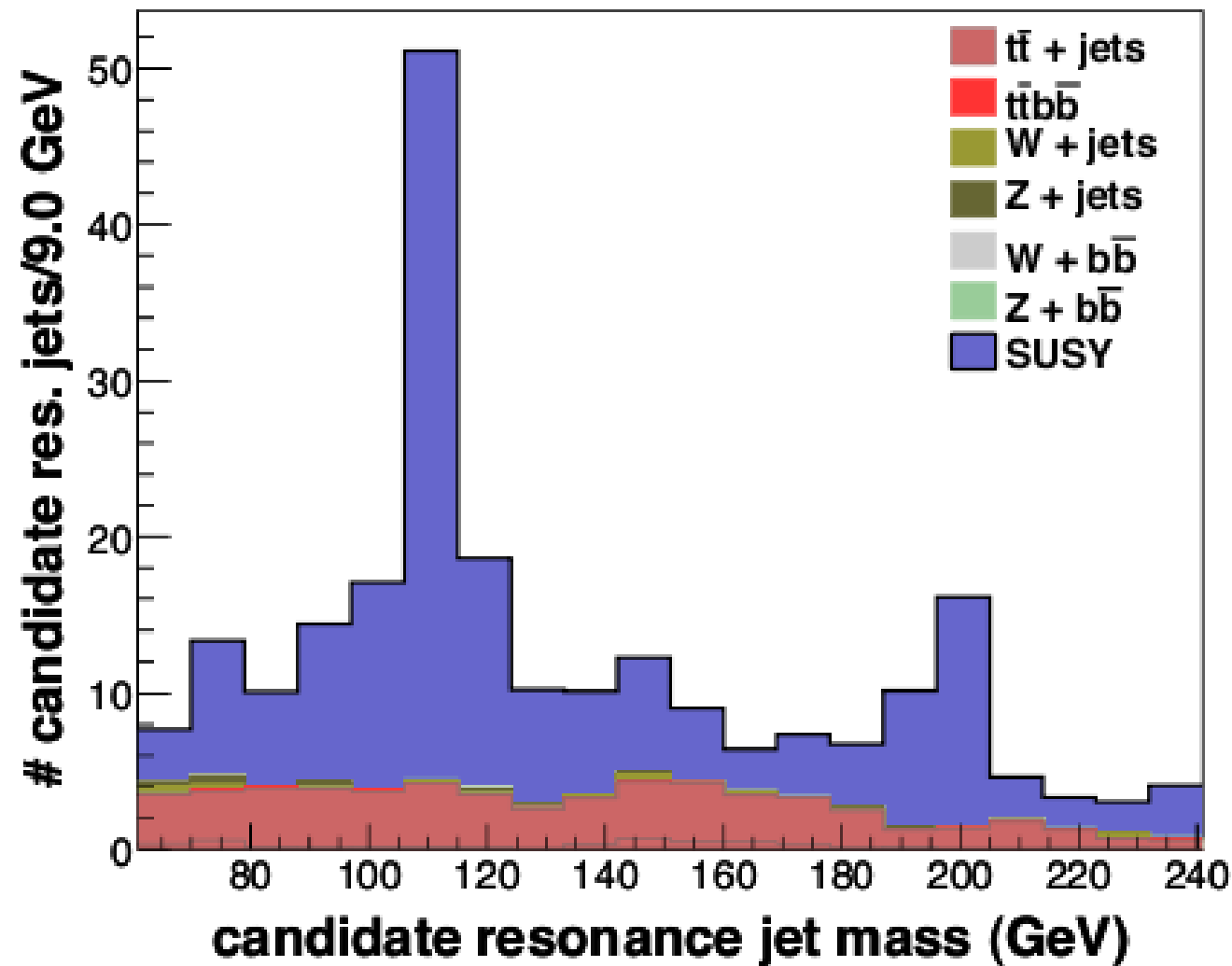
$H_T > 1 \text{ TeV}, \cancel{E}_T > 300 \text{ GeV}$   
 $4^+$  high- $p_T$  jets, no leptons  
 $2^+$  b-tags

(Stolen from A. Martin slides)

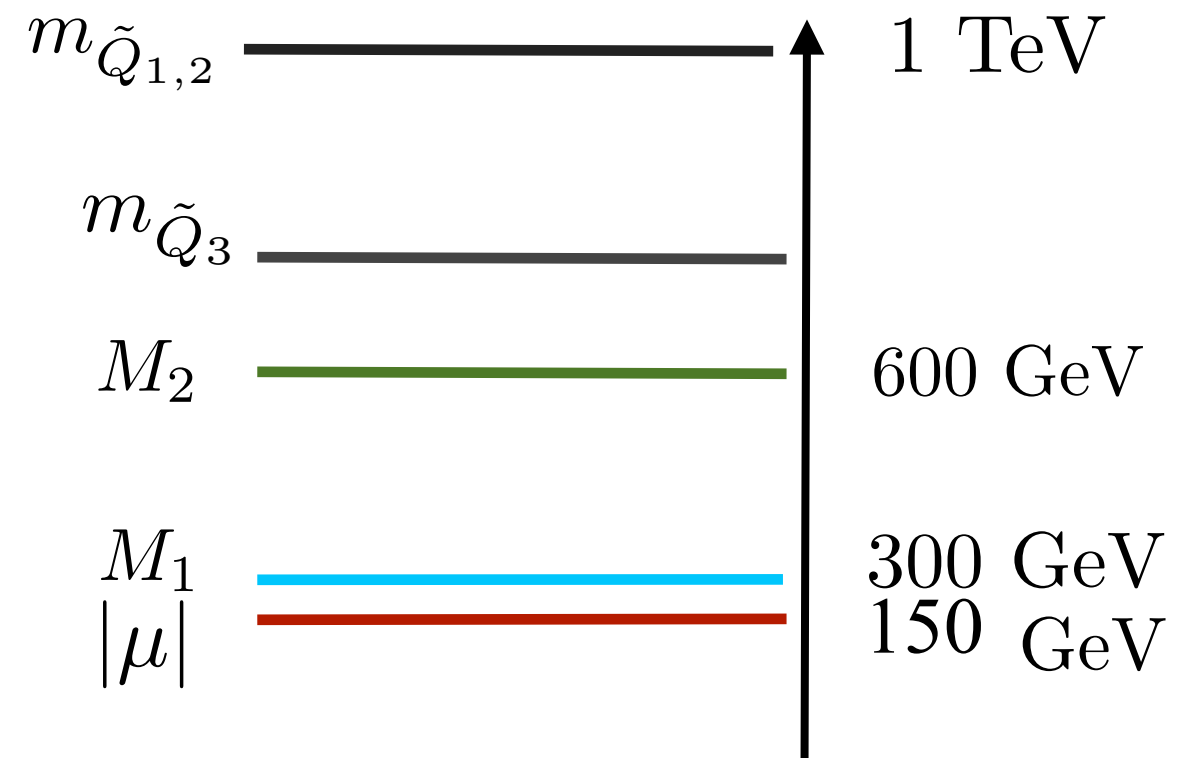
\*not totally fair

# Example 2: MSSM with $m_A = 200$ GeV

10 fb<sup>-1</sup> @ 14 TeV

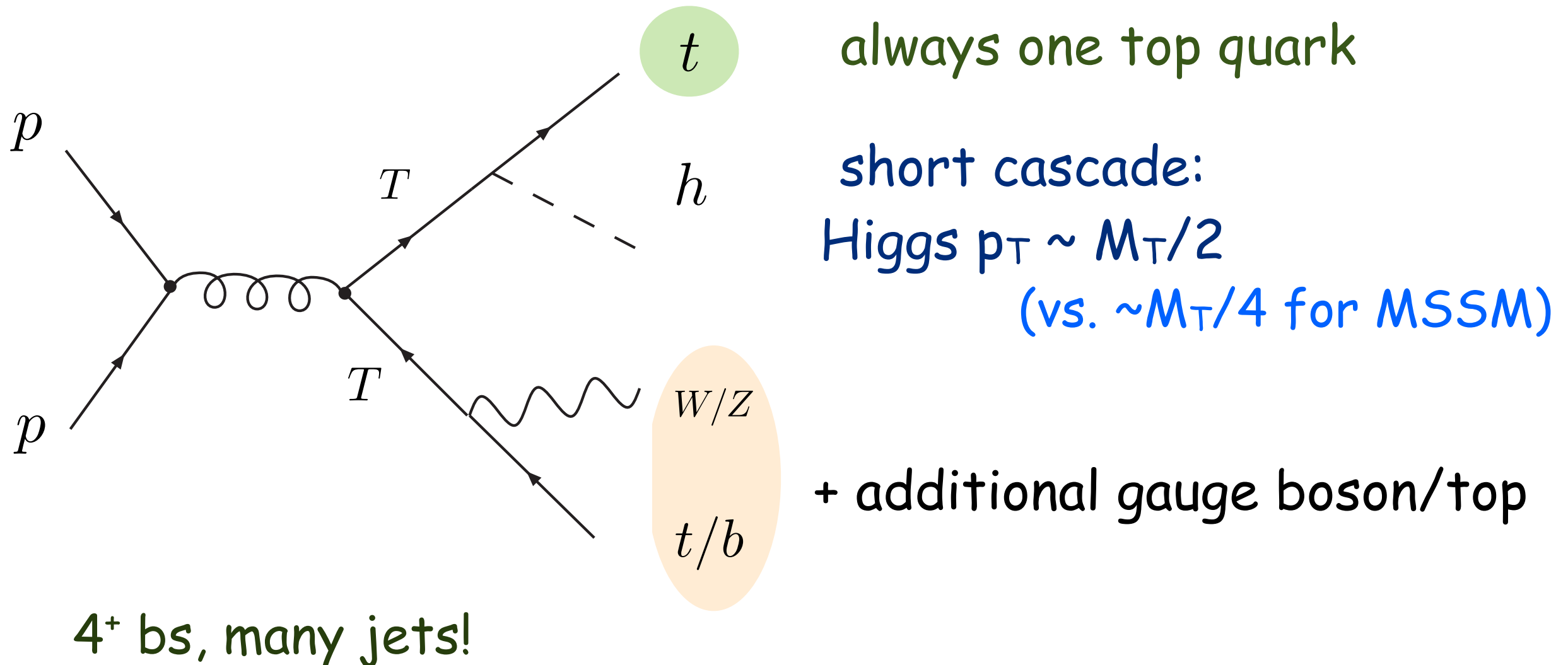


GK, Martin, Roy, Spannowsky; 1006.1656



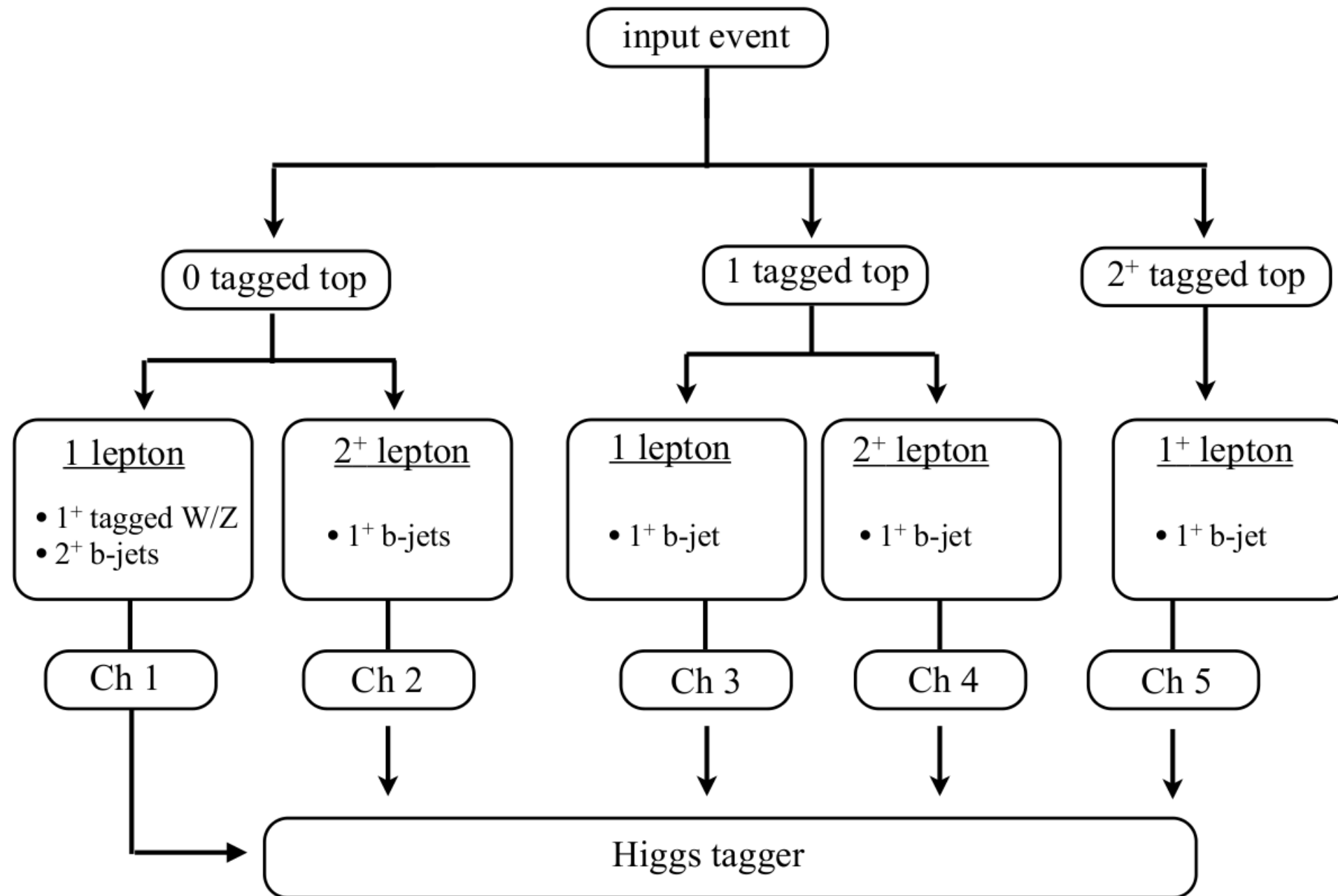
Could discover heavier A,H states!

# Example 3: Higgs from Top-Partners



Unlike SUSY, require multiple "tags" involving the varied final states, including boosted top and boosted W tagging.

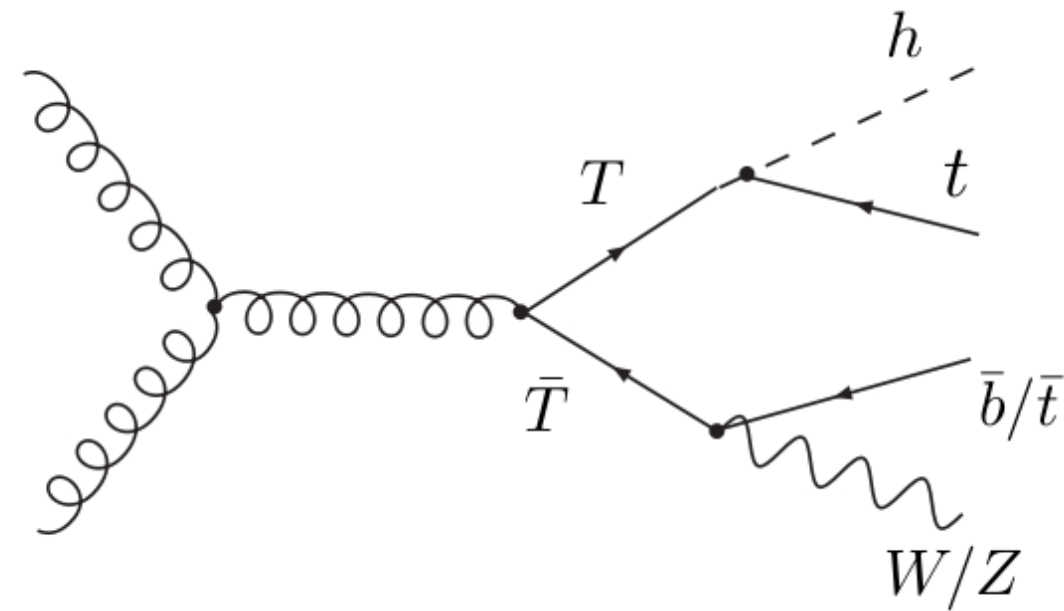
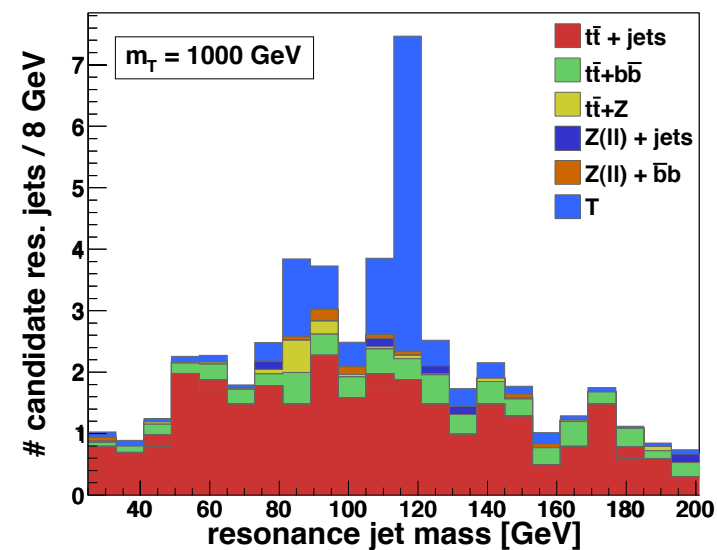
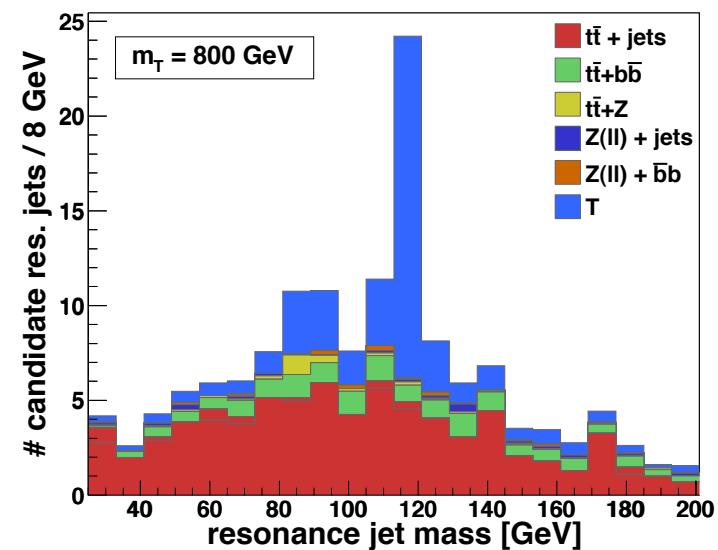
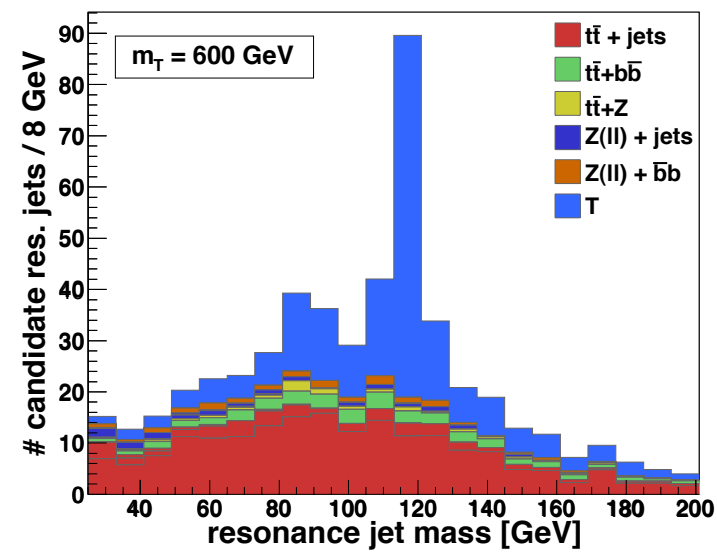
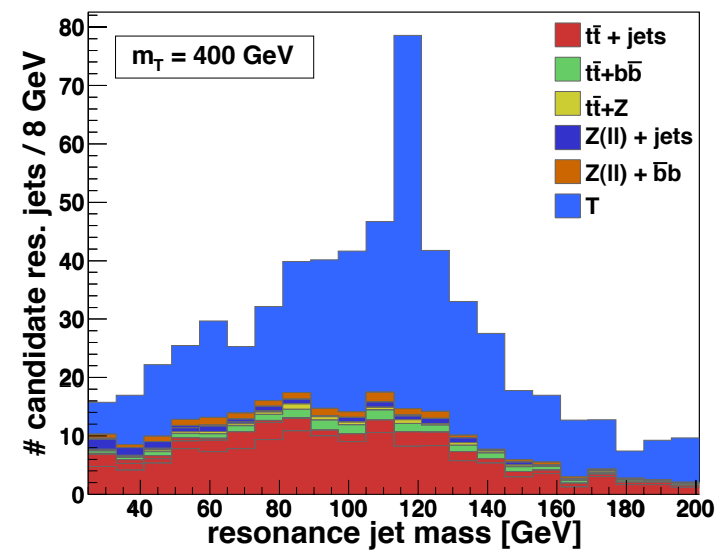
# Example 3: Higgs from Top-Partners



Different pathways better for different  $t'$  masses.

# Top partner production & decay:

10 fb<sup>-1</sup> @ 14 TeV



# Summary

- Jet substructure techniques are revolutionizing search for complicated hadronic final states
- MSSM  $h$  ideal candidate; large rate from squark production; large boost from cascade decay. Could discover  $h$  faster than SM!

Rethink  $m_A$  - $\tan(b)$  plane!!

- Top-partners produced with large rate; large boost; large decay fraction into Higgs; can also help discover and measure top-partner properties.
- Remarkable opportunities -- requires validation

"We"



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UW postdoc



Michael Spannowsky

UO->SLAC postdoc

"Discovering the Higgs Boson in New Physics Events using Jet Substructure"  
0912.4731 [PRD 2010]

"Discovering Higgs Bosons of the MSSM using Jet Substructure"  
1006.1656 [PRD 2010]

"Higgs Discovery through Top-Partners using Jet Substructure"  
1012.2866